The Arrival of Charm$^1$

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Abstract. Some of the theoretical motivations and experimental developments leading to the discovery of charm are recalled.

I INTRODUCTION

The discovery of charm was an exciting chapter in elementary particle physics. The theoretical motivations were strong, the predictions were crisp, and the experimental searches ranged from inadequate to serendipitous to inspired. Perhaps we can learn something relevant to present-day searches from those experiences. I would like to describe the evolution of the case for charm, some subsequent developments, and some questions which remain nearly a quarter of a century later.

The argument for charm was most compellingly made in the context of unification of the weak and electromagnetic interactions, briefly described in Sec. 2. Parallel arguments based on currents (Sec. 3) and quark-lepton analogies (Sec. 4) also played a role, while gauge theory results (Sec. 5) strengthened the case. In the early 1970’s, when electroweak theories began to be taken seriously, theorists began to exhort their experimentalist colleagues in earnest to seek charm (Sec. 6). In the fall of 1974, the discovery of the $J/\psi$ provided a candidate for the lowest-lying spin-triplet charm-anticharm bound state, and several other circumstances hinted strongly at the existence of charm (Sec. 7). Nonetheless, not everyone was persuaded by this interpretation, and it remained for open charm to be discovered before lingering doubts were fully resolved (Sec. 8).

Some progress in the post-discovery era is briefly noted in Sec. 9, while some current questions are posed in Sec. 10. A brief epilogue in Sec. 11 asks whether the search for charm offers us any lessons for the future. Part of the author’s interest in (recent) history stems from a review, undertaken with Val Fitch, of elementary particle physics in the second half of the Twentieth Century [1], which is to be issued in a second edition in a year or two.

1) Enrico Fermi Institute report EFI-98-54, November, 1998, hep-ph/9811359. To be published in Proceedings of the Workshop on Heavy Quarks at Fixed Target, Fermilab, Oct. 9–12, 1998.
II ELECTROWEAK UNIFICATION

The Fermi theory of beta decay [2] involved a pointlike interaction (for example, in the decay $n \rightarrow p + e^- + \bar{\nu}_e$ of the neutron). This feature was eventually recognized as a serious barrier to its use in higher orders of perturbation theory. By contrast, quantum electrodynamics (QED), involving photon exchange, was successfully used for a number of higher-order calculations, particularly following its renormalization by Feynman, Schwinger, Tomonaga, and Dyson [3].

Attempts to describe the weak interactions in terms of particle exchange date back to Yukawa [4]. A theory of weak interactions involving exchange of charged spin-1 bosons was written down by Oskar Klein in 1938 [5], to some extent anticipating that of Yang and Mills [6] describing self-interacting gauge particles. 

Once the $V - A$ theory of the weak interactions had been established in 1957 [7], descriptions involving exchange of charged vector bosons were proposed [8]. These tried to unify charged vector bosons (eventually called $W^\pm$) with the photon ($\gamma$) within a single SU(2) gauge symmetry. However, the (massless) photon couples to a vector current, while the (massive) $W$'s couple to a $V - A$ current. The SU(2) symmetry was inadequate to discuss this difference. Its extension by Glashow in 1961 [9] to an SU(2) × U(1) permitted the simultaneous description of electromagnetic and charge-changing weak interactions at the price of introducing a new neutral massive gauge boson (now called the $Z^0$) which coupled to a specific mixture of $V$ and $A$ currents for each quark and lepton.

The Glashow theory left unanswered the mechanism by which the $W^\pm$ and $Z$ were to acquire their masses. This was provided by Weinberg [10] and Salam [11] through the Higgs mechanism [12], whereby the SU(2) × U(1) was broken spontaneously to the U(1) of electromagnetism. Proofs of the renormalizability of this theory, due in the early 1970's to G. 't Hooft, M. Veltman, B. W. Lee, and J. Zinn-Justin [13], led to intense interest in its predictions, including the existence of charge-preserving weak interactions due to exchange of the hypothetical $Z^0$ boson. By 1973, a review by E. Abers and B. W. Lee [14] already was available as a guide to searches for neutral weak currents and other phenomena predicted by the new theory.

III CURRENTS

Let $Q_L^{(+)}$ be the spatial integral of the time-component of the charge-changing leptonic weak current, so that $Q_L^{(+)}|e^-\rangle_L = |\nu_e\rangle_L$, where the subscript $L$ denotes a left-handed particle. It is a member of an SU(2) algebra, since it is just an isospin-raising operator. Defining $Q_L^{(-)} = [Q_L^{(+)}]^\dagger$, we can form $2Q_L^{(\pm)} = [Q_L^{(+)}, Q_L^{(-)}]$ and then find that the algebra closes: $[Q_L^{(\pm)}, Q_L^{(\pm)}] = \pm Q_L^{(\pm)}$. In order to describe the decays of strange and non-strange hadrons in a unified way with a suitably normalized weak hadronic current, M. Gell-Mann and M. Lévy [15] proposed in 1960 that the corresponding hadronic charge behaved as $Q_h^{(+)}|n \cos \theta + \Lambda \sin \theta\rangle = |p\rangle$, with
\[ \sin \theta \simeq 0.2. \] Such a current also is a member of an SU(2) algebra. This allowed one to simultaneously describe the apparent suppression of strange particle decay rates with respect to strangeness-preserving weak interactions, and to account for small violations of weak universality in beta-decay, which had become noticeable as a result of radiative corrections [16].

In 1963 N. Cabibbo adopted the idea of the Gell-Mann – Lévy current by writing the weak current as

\[ J^{\mu(+)} = \cos \theta J^{\mu(+)}_{\Delta S=0} + \sin \theta J^{\mu(+)}_{\Delta S=1} \]  

(1)

and using the newly developed flavor-SU(3) symmetry [17] to evaluate its matrix elements between meson and baryon states. In the language of the \( u, d, s \) quarks this corresponded to writing the hadronic charge-changing weak currents as

\[
Q_h^{(+)}(\nu_e e^-) = \begin{bmatrix} 0 & \cos \theta & \sin \theta \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad Q_h^{(-)} = [Q_h^{(+)}]^\dagger, \quad Q_{3h} = \frac{1}{2}[Q_h^{(+)}, Q_h^{(-)}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\cos^2 \theta & -\sin \theta \cos \theta \\ 0 & -\sin \theta \cos \theta & -\cos^2 \theta \end{bmatrix} \]  

(2)

Again, the algebra closes: \( [Q_{3h}, Q_h^{(\pm)}] = \pm Q_h^{(\pm)} \), so the Cabibbo current is suitably normalized. A good fit to weak semileptonic decays of baryons and mesons was found in this manner, with \( \sin \theta \simeq 0.22 \).

As a student, I sometimes asked about the interpretation of \( Q_{3h} \), which has strangeness-changing pieces! A frequent answer, reminiscent of the Wizard of Oz, was: “Pay no attention to that [man behind the screen]!” The neutral current was supposed just to close the algebra, not to have physical significance.

### IV QUARK-LEPTON ANALOGIES: QUARTET MODELS

Very shortly after the advent of the Cabibbo theory, a number of proposals [18–20] sought to draw a parallel between the weak currents of quarks and leptons in order to remove the strangeness-changing neutral currents just mentioned. Since the electron and muon each were seen to have their own distinct neutrino [21], why shouldn’t quarks be paired in the same way? This involved introducing a quark with charge \( Q = 2/3 \), carrying its own quantum number, conserved under strong and electromagnetic but not weak interactions. As a counterpoise to the “strangeness” carried by the \( s \) quark, the new quantum number was dubbed “charm” by Bjorken and Glashow. The analogy then has the form

\[
\begin{bmatrix} \nu_e \\ e^- \end{bmatrix} \begin{bmatrix} \nu_\mu \\ \mu^- \end{bmatrix} \Leftrightarrow \begin{bmatrix} u \\ d \end{bmatrix} \begin{bmatrix} c \\ s \end{bmatrix}. \]  

(3)
The matrix elements of the hadronic $Q^{(+)}$ (we omit the subscript $h$) were then
\begin{equation}
⟨u|Q^{(+)}|d⟩ = ⟨c|Q^{(+)}|s⟩ = \cos θ , \quad ⟨u|Q^{(+)}|s⟩ = −⟨c|Q^{(+)}|d⟩ = \sin θ , \quad (4)
\end{equation}
while those of $Q_3$ were
\begin{equation}
⟨u|Q_3|u⟩ = ⟨c|Q_3|c⟩ = −⟨d|Q_3|d⟩ = −⟨s|Q_3|s⟩ = \frac{1}{2} , \quad (5)
\end{equation}
with all off-diagonal (flavor-changing) elements equal to zero. Here, as before, $\sin θ ≃ 0.22$. Bjorken and Glashow were the first to call the isospin doublet of non-strange charmed mesons “D” (for “doublet”), with $D^0 = c\bar{u}$ and $D^+ = c\bar{d}$.

V GAUGE THEORY RESULTS

The promotion of electroweak unification to a genuine gauge theory permitted quantitative predictions of the properties of the fourth quark.

A The Glashow-Iliopoulos-Maiani (“GIM”) paper

Taking his gauge theory of electroweak interactions seriously, Glashow in 1970 together with J. Iliopoulos and L. Maiani observed that the quartet model of weak hadronic currents banished flavor-changing neutral currents to leading order of momentum in higher orders of perturbation theory [22]. Thus, for example, higher-order contributions to $K^0-\bar{K}^0$ mixing, expected to diverge in the $V-A$ theory or in a gauge theory without the charmed quark, would now be cut off by $m_c$, where $m_c$ is the mass of the charmed quark. In this manner an upper limit on the charmed quark mass of about 2 GeV was deduced. In view of the predominant coupling (4) of the charmed quark to the strange quark, charmed particles should decay mainly to strange particles, with a lifetime estimated to be about $τ_{charm} ≃ 10^{-13}$ s.

The GIM paper contained a number of other specific predictions about the properties of charmed particles. Among these were:

- A branching ratio of the charmed meson $D^0 = c\bar{u}$ to $K^-\pi^+$ of a few percent;
- Strong production of charm-anticharm pairs;
- Direct leptons in charm decays;
- Charm production in neutrino reactions;
- Neutral flavor-preserving currents;
- The observability of a $Z^0$ in the direct channel of $e^+e^−$ annihilations.

These were all to be borne out over the next few years. The discovery of the $Z^0$ took longer, and was first made in a hadron rather than a lepton collider [23].
B Anomalies

Once the electroweak theory was on firm theoretical grounds, it was noticed by several authors in 1972 [24–26] that contributions to various triangle diagrams involving fermion loops had to cancel. For the electroweak theory it was sufficient to consider the sum over all fermion species of $I_{3L}Q^2$, where $I_{3L}$ is the weak isospin of the left-handed states and $Q$ is their electric charge. For the first family of quarks and leptons the cancellation is arranged as follows:

| Fermion | $\nu_e$ | $e^-$ | $u$ | $\bar{d}$ | Sum |
|---------|---------|-------|-----|-----------|-----|
| Contribution | $\frac{1}{2}(0)^2$ | $-\frac{1}{2}(-1)^2$ | $\frac{1}{2}(3)\left(\frac{2}{3}\right)^2$ | $-\frac{1}{2}(3)\left(-\frac{1}{3}\right)^2$ | 0 |
| Equal to | 0 | $-\frac{1}{2}$ | $\frac{2}{3}$ | $-\frac{1}{6}$ | 0 |

The corresponding cancellation for the second family reads

$$\nu_\mu + \mu + c + s = 0 \ ,$$

so that the charmed quark was required for such a cancellation, given the existence of the muon and the strange quark.

C Rare kaon decays

In a landmark 1973 paper, M. K. Gaillard and B. W. Lee [27] took the charmed quark seriously in calculating a host of processes involving kaons to higher order in the new electroweak theory. These included $K^0-\bar{K}^0$ mixing and numerous rare decays such as $K_L \rightarrow (\mu^+\mu^-, \gamma\gamma, \pi^0 e^+ e^-, \pi^0 \nu\bar{\nu}, \ldots)$ and $K^+ \rightarrow (\pi^+ e^+ e^-, \pi^+ \nu\bar{\nu}, \ldots)$. The analyses of $K^0-\bar{K}^0$ mixing and $K_L \rightarrow \mu^+\mu^-$ indicated that $m_c^2 - m_u^2$ obeyed a strong upper bound, while the failure of $K_L \rightarrow \gamma\gamma$ to be appreciably suppressed indicated that $m_u^2 \ll m_c^2$. Together these results supported the GIM estimate of $m_c \leq 2$ GeV and considerably strengthened an earlier bound by Lee, J. Primack, and S. Treiman [28].

VI EXHORTATIONS

K. Niu and collaborators already had candidates for charm in emulsion as early as 1971 [29]. These results, taken seriously by theorists in Japan [30,31], will be mentioned again presently. Meanwhile, in the West, theorists besides GIM began to urge their experimental colleagues to find charm. C. Carlson and P. Freund [32] discussed, among other things, the properties of a narrow charm-anticharm bound state. George Snow [33] listed a number of features of charm production and decays. Through an interest in hadron spectroscopy, I became involved late in 1973 in these efforts in collaboration with Gaillard and Lee. We started to look at charm production and detection in hadron, neutrino, and electron-positron...
reactions. It quickly became clear that a new quark, even one as light as 2 GeV, could have been overlooked.

Glashow spoke on charm at the 1974 Conference on Experimental Meson Spectroscopy, held at Northeastern University [34]. In addition to the properties mentioned in the earlier GIM paper, he told his experimental colleagues to expect:

- Charm lifetimes ranging between $10^{-13}$ and $10^{-12}$ s;
- Comparable branching ratios for semileptonic and hadronic decays;
- An abundance of strange particles in the final state;
- Dileptons in neutrino reactions (with the second lepton due to charm decay).

He ended with the following charge to his colleagues:

**WHAT TO EXPECT AT EMS-76**

There are just three possibilities:

1. Charm is not found, and I eat my hat.
2. Charm is found by hadron spectroscopers, and we celebrate.
3. Charm is found by outlanders, and you eat your hats.

In the summer of 1974, Sam Treiman, then an editor of Reviews of Modern Physics, pressed Ben Lee, Mary Gaillard, and me to write up our results with the comment: “It’s getting urgent.” Our review of the properties of charmed particles was eventually published in the April 1975 issue [35]. Better late than never. By then we were able to add an appendix dealing with the new discoveries. The body of our article (“GLR”) was written before them. Our conclusions, most of which I mentioned at a Gordon Conference late in the summer of 1974, were as follows:

We have suggested some phenomena that might be indicative of charmed particles. These include:

(a) ‘‘direct’’ lepton production,
(b) large numbers of strange particles,
(c) narrow peaks in mass spectra of hadrons,
(d) apparent strangeness violations,
(e) short tracks, indicative of particles with lifetime of order $10^{-13}$ sec.,
(f) di-lepton production in neutrino reactions,
(g) narrow peaks in $e^+e^-$ or $\mu^+\mu^-$ mass spectra,
(h) transient threshold phenomena in deep inelastic leptoproduction,
(i) approach of the $(e^+e^- \rightarrow \text{hadrons})/(e^+e^- \rightarrow \mu^+\mu^-)$ ratio [‘‘$R’’’] to $3^{1/3}$, perhaps from above, and
(h) any other phenomena that may indicate a mass scale of 2 - 10 GeV.
A couple of these bear explanation. “Apparent strangeness violations” can occur in the transitions $c \leftrightarrow d$; otherwise strangeness would directly track charm (aside from a sign; the convention is that the strangeness of an $s$ quark is $-1$, while the charm of a charmed quark is $+1$). “Narrow peaks in $e^+e^- \text{ or } \mu^+\mu^-$ mass spectra” were not just dreamt up out of the blue; we were aware of an effect in muon pairs at a mass around 3.5 GeV [36] which could have been the lowest spin-triplet $c\bar{c}$ bound state. John Yoh remembers hearing this interpretation from Mary K. Gaillard in the Fermilab cafeteria in August of 1974. Our estimate of the width of this state was about 2 MeV, based on extrapolating the Okubo-Iizuka-Zweig (OZI) rule [37] which suppressed “hairpin” quark diagrams. An early prediction by T. Appelquist and H. D. Politzer [38] of the properties of $c\bar{c}$ bound states used QCD to anticipate a narrower spin-triplet than GLR.

I invited Glashow to the University of Minnesota in October of 1974 to speak on charm and much else (including grand unified theories, which he was then developing with Howard Georgi [39]). An unpersuaded curmudgeonly astronomer turned to a younger colleague in the audience, whispering: “When do they bring in the men in white coats?” The timing could not have been better. Charm was to be discovered within a month.

\section*{VII HIDDEN (AND NOT-SO-HIDDEN) CHARM}

As was suspected even before the days of QCD and asymptotic freedom, the ratio $R \equiv \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ probes the sum $\sum Q^2$ of the squared charges of quarks pair-produced at a given c.m. energy. Thus, above the resonances $\rho$, $\omega$, and $\phi$ which are features of low-energy $e^+e^-$ annihilations into hadrons, one expected to see $R = 3[(2/3)^2 + (-1/3)^2 + (-1/3)^2] = 2$, corresponding to the three light quarks $u$, $d$, and $s$. With wide errors, the ADONE Collider at Frascati found this to be the case. (See [40] for earlier references.)

In 1972 the Cambridge Electron Accelerator (CEA) was converted to an electron-positron collider. At energies above 3 GeV the cross section for $e^+e^- \rightarrow \text{hadrons}$, instead of falling with the expected $1/E_{\text{c.m.}}^2$ behavior characteristic of pointlike quarks, was found to remain approximately constant [41]. At $E_{\text{c.m.}} = 4$ GeV, $R$ was $4.9 \pm 1.1$, while it rose to $6.2 \pm 1.6$ at $E_{\text{c.m.}} = 5$ GeV [42]. These results were confirmed, with higher statistics, at the SPEAR machine [42]. At the 1974 International Conference on High Energy Physics, Burt Richter voiced concern about the validity of the naive quark interpretation of $R$.

The London Conference was distinguished by various precursors of charm in addition to the rise in $R$ just mentioned. Deep inelastic scattering of muon neutrinos was occasionally seen (in about 1% of events) to lead to a pair of oppositely-charged muons. One muon carried the lepton number of the incident neutrino; the second could be the prompt decay product of charm. This interpretation was mentioned by Ben Lee at the end of D. Cundy’s rapporteur’s talk [43]. Leptons produced at large transverse momenta [44] were due in part to prompt decays of charmed
particles. John Iliopoulos [45] not only laid out a number of the predictions for properties of charmed particles, but bet anyone a case of wine that they would be discovered by the next (1976) International Conference on High Energy Physics. Though he recalls several takers, they never paid off.

On November 11, 1974, the simultaneous discovery of the lowest-lying $^3S_1$ charm-anticharm bound state, with a mass of 3.1 GeV/$c^2$, was announced by Samuel C. C. Ting and Burt Richter. Ting’s group, inspired in part by the suggestion of a peak in an earlier experiment [36] and in part by an innate confidence that lepton-pair spectra would reveal new physics, collided protons produced at the Brookhaven Alternating-Gradient Synchrotron (AGS) with a beryllium target to produce electron-positron pairs whose effective mass spectrum was then studied with a high-resolution spectrometer [46]. The new particle they discovered was called “J” (the character for “Ting” in Chinese). Richter’s group, working at SPEAR, wished to re-check anomalies in the cross section for electron-positron annihilations that had shown up in earlier running around a center-of-mass energy of 3 GeV. By carefully controlling the beam energy, they were able to map out the peak of a narrow resonance at 3.1 GeV [47], which they called “ψ”, a continuation of the vector-meson series $\rho, \omega, \phi, \ldots$. The dual name $J/\psi$ has been preserved. I was made aware of these discoveries by a call from Ben Lee on November 11. They certainly looked like charm to me, as well as to a number of other people [38,48].

However, a large portion of the community offered alternative interpretations [49]. Some potential objections to charm (see the next Section) were worth putting to experimental tests (e.g., by finding singly-charmed particles [50]). However, I doubt the situation was ever as grave as implied by the comment made to me in March of 1975 by Dick Blankenbecler at SLAC:

Don’t give up the ship. It has just begun to sink.

VIII OPEN CHARM

In 1971, well before the discovery of the $J/\psi$, there were intimations of particles carrying a single charmed quark through the short tracks they left in emulsions, as studied by K. Niu and collaborators at Nagoya [29]. The best candidate appears now to be an example of the rare decay $D^+ \rightarrow \pi^+\pi^0$. Tony Sanda reminded us in this meeting [51] that by the 1975 International Conference on Cosmic Ray Physics this group had accumulated [52] a significant sample of such “short-lived particles.”

A candidate for the charmed baryon now called $\Lambda_c$ (as well as for the decay $\Sigma_c \rightarrow \Lambda_c\pi$) was reported in neutrino interactions in 1975 [53]. The properties of the $\Lambda_c$ and $\Sigma_c$ were very close to those anticipated by an analysis of charmed-particle spectroscopy [54] which appeared shortly after the discussion of the $J/\psi$.

Despite these indications, as well as the discovery of a candidate for the first radial excitation (“ψ′”) of the $J/\psi$ [55] just 10 days after the observation of the $\psi$ in $e^+e^-$ collisions, the charm interpretation of the $J/\psi$ and ψ′ required several key tests to be passed.
A Where was the $D \to \bar{K}\pi$ decay?

The decays of charmed nonstrange mesons, with predicted masses of nearly 2 GeV/$c^2$, could involve a wide variety of final states, so that any individual two-body (e.g., $D^0 \to K^-\pi^+$) or three-body (e.g., $D^+ \to K^-\pi^+\pi^+$) mode should have a branching ratio of a few percent [22].

GLR attempted to estimate this effect using a current algebra model to estimate multiple-pion production [35]. Unfortunately we used a value of the pion decay constant $f_\pi$ high by $\sqrt{2}$ [56], and neglected other modes besides $\bar{K} + n\pi$ [57]. Our results implied $\mathcal{B}(D^0 \to K\pi)$ of nearly 50% for a 2 GeV/$c^2$ charmed particle, clearly an overestimate both in hindsight and intuitively (see, e.g., [22]). Our result was quoted in the report [58] of an initial SPEAR search which failed to find charmed particles, and may have led to overconfidence in some other proposed experiments [59] which failed to find charm. Subsequent calculations (also taking into account non-zero pion mass), based both on the current algebra matrix element and on a statistical model [60], found smaller $D \to \bar{K}\pi$ branching ratios than GLR [56].

B Why did $R$ rise beyond its predicted value of $3^{1/3}$?

The rise in $R$ observed at 4 GeV and higher was too large to account for charm, which predicted $\Delta R = 3Q^2_c = 4/3$. The resolution of this problem was that pairs of $\tau$ leptons [61], whose threshold is $E_{\text{c.m.}} = 2m_\tau c^2 \simeq 3.56$ GeV, were also contributing to $R$. These $\tau$ leptons also diluted the rise in kaon multiplicity expected above charm threshold. This coincidence had all the aspects of a mystery thriller [62]; the near-degeneracy of charm and $\tau$ production thresholds is one of those effects (like the comparable masses of the muon and pion) that seems just to have been put in to make the problem harder.

The value of $R$ is still a bit large in comparison with theoretical expectations in the range covered by SPEAR [63].

C Where were the predicted electric dipole transitions from the $\psi'$ to P-wave levels?

The lowest P-wave charmonium levels (now called $\chi_c$) were predicted to lie between the 1S and 2S levels [64]. Thus, one expected to be able to see the electric dipole transitions $\psi' \to \gamma\chi_c$, leading to monochromatic photons. Initial inclusive searches using a NaI(Tl) detector at SPEAR did not turn up these transitions [65], leading to some concern.

The problem turned out to be more experimentally demanding than originally suspected. By looking for the cascade transitions $\psi' \to \gamma\chi_c \to \gamma\gamma J/\psi$, the DASP group, working at the DORIS storage ring at DESY, presented the first results [66] for the $\chi_{c1} = {}^3P_1$ level (with some possible admixture of $\chi_{c2} = {}^3P_2$). By
looking for events of the form $\psi' \rightarrow \gamma \chi_c \rightarrow \gamma + (\pi\pi, K\bar{K}, \ldots)$ and reconstructing the mass of the final hadronic state, the Mark I group at SPEAR [67] detected states corresponding to both $\chi_{c2}$ and $\chi_{c0} = ^3P_0$.

**D  Discovery of the $D$ mesons**

By 1975, estimates based on the mass of the $J/\psi$, on QCD [54], and on potential models incorporating coupled-channel effects [68] predicted $D$ masses in the range of 1.8 to 1.9 GeV/$c^2$, so that the rise in $R$ could, at least in part, be accounted for by $DD$ threshold. Glashow urged Gerson Goldhaber to re-examine the negative search results [69]. Together with F. M. Pierre and other collaborators, Goldhaber incorporated time-of-flight information to improve kaon identification, and found peaks in $D^0 \rightarrow K^-\pi^+$ and $K^-\pi^+\pi^-\bar{\pi}^+ [70]$, corresponding to a mass which we now know to be 1.863 GeV/$c^2$. Low-multiplicity decays of the $D^+$ were also seen shortly thereafter [71].

The first discoveries of $D$ mesons were announced in June of 1976. This would have been too late for the 1976 Meson Conference, which was traditionally held in April, so Glashow could have lost his bet made at the 1974 Conference [34]. (See, however, [53].) But meson spectroscopy was entering a slower period, and the next conference was not held until 1977. Since charm had clearly been discovered by outlanders, the participants were obliged to eat their (candy) hats, graciously distributed by the conference organizers.

**E  The $\tau$ as interloper**

What about the $\tau$ lepton, whose appearance complicated the interpretation of the SPEAR results? It destroyed the anomaly cancellation, mentioned earlier! As a result, a new pair of quarks with charges $2/3$ and $-1/3$, named top and bottom by Harari [62], had to be postulated. Just such a quark pair had been invented earlier (in 1973) by Kobayashi and Maskawa [31] in order to explain the observed CP violation in kaon decays. The discovery of these quarks is another story, of which Fermilab has a right to be proud but which we shall not mention further here.

**F  Total rate vs. purity in charm detection**

A question which arose in the search for charmed particles is being played out again as present and future searches are planned. Is it better to work in a relatively clean environment with limited rate, or in an environment where rate is not a problem but backgrounds are high? For charm in the mid-1970’s, the choice lay between the reaction $e^+e^- \rightarrow \gamma^* \rightarrow c\bar{c}$, contributing $\Delta R = 4/3$ above charm threshold, and fixed-target proton-proton collisions at 400 GeV/$c^2$, with $\sigma_{c\bar{c}} = \mathcal{O}(10^{-3})\sigma_{\text{tot}}$ but
overall greater charm production rates than in $e^+e^-$ collisions. (The CERN Intersecting Storage Rings (ISR) were also running at that time, providing proton-proton c.m. energies of up to 63 GeV but with limited rates compared to fixed-target experiments.)

After much time and effort, the balance eventually tipped in favor of fixed target hadron (or photon) collisions. (In photon collisions the photon can couple directly to a charm-anticharm pair via the electric charge, leading to diffractive production.) Two advances that greatly enhanced the ability to isolate charm were the use of the soft pion in $D^* \rightarrow D\pi$ decays [72] and the impressive growth in vertex detection technology [73].

Soft pion tagging. The lowest-lying $^1S_0$ and $^3S_1$ bound states of a charmed quark and a nonstrange antiquark are called $D$ and $D^*$, respectively. Their masses are such that $D^{*0}$ can decay to $D^0\gamma$ and just barely to $D^0\pi^0$, while $D^{*+}$ can decay to $D^{0}\gamma$ and just barely to $D^{+}\pi^0$ or $D^0\pi^+$. In the last case, the charged pion has a very low momentum with respect to the $D^0$, and can be used to “tag” it. One takes a hypothetical set of $D^0$ decay products and combines them with the “tagging” pion. If the decay products really came from a $D^0$, the difference in effective masses of the products with and without the extra pion should be $M(D^{*+}) - M(D^0) \approx 145$ MeV/$c^2$. This method not only can help to see the $D^0$, but can tell whether it was produced as a $D^0$ or a $\bar{D}^0$, since the only low-mass combinations are $\pi^+D^0$ or $\pi^-\bar{D}^0$. This distinction is important if one wishes to study $D^0-\bar{D}^0$ mixing or suppressed decay modes of the $D^0$ (where the flavor of the decay products does not necessarily indicate the flavor of the decaying state).

Vertex detection. The earliest technique for detecting the short tracks made by charmed particles, nuclear emulsions, was successfully used in Fermilab E-531 for the detection of charmed particles produced in neutrino interactions, has been used by Fermilab E-653 for the study of decays of charmed and $B$ mesons, and is still in use for detecting decays of $\tau$ leptons produced in neutrino-oscillation experiments [74]. It has profited greatly from automatic scanning methods introduced by Niu’s group at Nagoya. Still, it can be subject to systematic errors, such as a bias against long neutral decay paths.

When it was realized that charmed particles could have lifetimes less than $10^{-12}$ s, numerous attempts were made to improve the resolution of existing devices such as bubble chambers and streamer chambers. Some of these are described in [73].

In the late 1970’s, electronic spectrometers such as the OMEGA spectrometer at CERN began to be equipped with new, high-resolution silicon vertex detectors. These devices had the advantages of radiation hardness, excellent spatial resolution, and electronic readout, making them the technique of choice for resolving the tracks of short-lived particles in the busy environments of hadro- and electro-production. Experiments which have profited from this technique over the years include CERN WA-82, WA-89, WA-92 and Fermilab E-687, E-691, E-769, E-791, and E-831 (FOCUS).
TABLE 1. Lowest orbitally-excited charmed mesons.

| \( j \)  | \( J = j - \frac{1}{2} \) state | \( J = j + \frac{1}{2} \) state | \( l(D^{(*)}\pi) \) Width |
|--------|---------------------------------|---------------------------------|-------------------------|
| \( \frac{1}{2} \) | \(? \rightarrow D\pi\) | \(? \rightarrow D^*\pi^a\) | 0 | Broad |
| \( \frac{3}{2} \) | \(D(2420) [\rightarrow D^*\pi]\) | \(D(2460) [\rightarrow D^{(*)}\pi]\) | 2 | Narrow |

\(^{a}\)Candidate exists (see below).

IX EXAMPLES OF FURTHER PROGRESS

A Emulsion results

Emulsion studies of neutrino- and hadroproduction of charmed particles have displayed the variation of lifetimes among charmed particles, measured the decay constant \( f_{D_s} \) of the charmed-strange meson \( c\bar{s} \equiv D_s \), and set limits on neutrino oscillations. The scanning techniques pioneered by the Nagoya group are beginning to be disseminated so that many institutions can analyze future results.

B Excited charmed mesons

A meson containing a single heavy quark and a light antiquark is like a hydrogen atom of the strong interactions. The heavy quark corresponds to the nucleus, while the antiquark (and its accompanying glue) correspond to the electron and electromagnetic field.

The lowest orbitally excited states of charmed mesons follow an interesting pattern rather different from that in charm-anticharm bound states. In \( c\bar{c} \) levels, the charge-conjugation parity \( C = (-1)^{L+S} \) prevents the mixing of spin-singlet and spin-triplet levels with the same \( L \). Thus, the properties of levels are best calculated by first coupling the \( c \) and \( \bar{c} \) spins to \( S = 0 \) or \( 1 \) and then coupling \( S \) with the orbital angular momentum \( L \) to total angular momentum \( J \). One thus labels the states by \( 2^{S+1}[L]_J \), where \([L] \equiv S, P, D, F, \ldots \) for \( L = 0, 1, 2, 3, \ldots \). In heavy-light states, however, nothing prevents mixing of \( ^1P_1 \) and \( ^3P_1 \) levels, and there is a favored pattern in the limit that the heavy quark’s mass approaches infinity [54,75,76]. One first couples the light antiquark’s spin \( s = 1/2 \) to the orbital angular momentum \( L = 1 \) to obtain the total angular momentum \( j = 1/2, 3/2 \) carried by the light quark. One then couples \( j \) to the heavy quark’s spin \( S_Q = 1/2 \) to obtain two pairs of levels, as shown in Table 1.

The \( j = 1/2 \) states are expected to decay to \( D^{(*)}\pi \) via S-waves and thus to be broad and hard to find, while the \( j = 3/2 \) states should decay via D-waves and thus should be narrower and more easily distinguished from background. The first orbitally excited charmed mesons were reported by the ARGUS Collaboration [77] in 1985. Since then, considerable progress has been made on these states by the ARGUS, CLEO, LEP, and fixed-target Fermilab collaborations, with the properties
of the $j = 3/2$ states well mapped out. There is now a candidate for a broad
$(j = 1/2)$ state, with spin-parity $J^P = 1^+$, mass $M = 2.461^{+0.041}_{-0.034} \pm 0.010 \pm 0.032$
GeV, and width $\Gamma = 290^{+101}_{-79} \pm 26 \pm 36$ MeV [78].

\section*{C Charmonium with antiprotons}

The ability to control the energy of an antiproton beam, first in the CERN
ISR [79] and then in the Fermilab Antiproton Accumulator Ring [80], permitted
the study of charmonium states through direct-channel production on a gas-jet
target. A series of experiments studied the production and decay of states like
the $\eta_c$ (the $1S_0$ charmonium ground state), the $J/\psi$, and the $\chi_c$ levels, and led to
the discovery of the $h_c$, the $1P_1$ level. Precise measurements of masses and decay
widths were made, and an earlier claim [81] for the $2^1S_0$ level, the $\eta'_c$, has been
disproved. The search for this state, as well as for possible narrow $c\bar{c}$ levels above
$D\bar{D}$ threshold, continues at Fermilab as well as elsewhere (see, e.g., [82]).

\section*{D Photo- and hadroproduction with vertex detection}

An impressive series of fixed-target experiments has refined the technique of
vertex detection using silicon strips or pixels [83], obtaining unparalleled numbers
of charmed particles. Among the significant results are detailed studies of lifetime
differences among charmed particles, ranging from greater than $10^{-12}$ s for the $D^+$
to less than $10^{-13}$ s for the $\Omega_c = c\bar{s}s$.

\section*{E Electron-positron collisions}

The ARGUS and CLEO Collaborations continued to contribute significant results
on charmed particles produced in $e^+e^-$ collisions, with results still flowing from
CLEO on such topics as the leptonic decay of the $D_s$ [84] and the spectroscopy of
charmed baryons [85].

\section*{X EXAMPLES OF CURRENT QUESTIONS}

\subsection*{A Lifetime hierarchies}

The charmed-particle lifetimes mentioned in the previous Section, with
\[ \tau(\Omega_c) < \tau(\Lambda_c) < \tau(D^0) \simeq \tau(D_s) < \tau(D^+) \tag{7} \]
varying by more than a factor of 10, continue to be a mild source of concern to
theorists. The above hierarchy is better-understood [86,87] than that in strange
particle decays, where lifetimes vary by more than a factor of 600 $\simeq \tau(K_L)/\tau(K_S)$. 
However, the same methods which appear to have described the charm lifetime hierarchy do not explain why $\tau(\Lambda_b)/\tau(B^{+,0}) < 0.8$, whereas a ratio more like 0.9 to 0.95 is expected. It appears that non-perturbative effects, probably the main feature of the lifetime differences for kaons and still important for charmed particles, continue to have some residual effects even for the decays of the heavy $b$ quark.

## B Decay constants

The latest average for the $D_s$ decay constant [88] is $f_{D_s} = 255 \pm 21 \pm 28$ MeV, based on observation of the decays $D_s \rightarrow \mu\nu, \tau\nu$. We still need the values of the other heavy meson decay constants: $f_D, f_B,$ and $f_{B_s}$. Lattice [89] and QCD sum rule [90] predictions for these quantities exist. The value of $f_{D_s}$ is consistent with predictions, though a bit on the high side. The value of $f_D$ is in principle accessible with present CLEO data samples [91]. One would like to be able to distinguish between the quark-model prediction [92] $f_{D_s}/f_D \approx 1.25$ and the lattice/sum rule predictions of this ratio, which range between 1.1 and 1.2. One may be able to isolate $D^+ \rightarrow \mu^+\nu_\mu$ via the kinematics of the decay $D^{*+} \rightarrow \pi^0D^+$ [93].

## C Excited $D$ mesons

Using heavy-quark symmetry, we can relate the properties of a meson containing a heavy quark $Q$ and a light antiquark $\bar{q}$ to those where $Q$ is replaced by another heavy quark $Q'$. Thus, further study of excited $D = c\bar{q}$ mesons would give us information about the corresponding $\bar{B} = b\bar{q}$ states. The properties of P-wave $b\bar{q}$ ("$B^{**}$") mesons would be very useful for "tagging" neutral $B$’s [94], since a $\bar{B}^0$ resonates with a $\pi^-$ to form a $B^{**-}$ while a $\bar{B}^0$ resonates with a $\pi^+$ to form a $B^{**+}$.

## D Charm-anticharm mixing and CP violation

Both mixing and CP-violating effects are expected to be far smaller for charmed particles than for $B$’s [95]. Since these effects are easier to study in the charm system (at least in hadronic production, where charm production is much easier than $b$ production), they are thus ideal for displaying beyond-standard-model physics, since the standard-model effects are so much smaller.

## XI LESSONS?

Should we be learning from history, or will we always be fighting the last war? The search for charm has possible lessons, perhaps to be taken with a grain of salt, for theory, experiment, and their synthesis in the form of future searches.
A Theory

The optimism of theorists was justified in the search for charm. The charmed quark indeed was light, $m_c \simeq 1.5 \text{ GeV}/c^2$. Perturbative QCD was at least a qualitative guide to the properties of charmonium and charmed particles. The discovery of the first quark with mass substantially exceeding that of the QCD scale was a tremendous boost to the idea (already strongly suggested by deep inelastic scattering) that fundamental quarks needed to be taken seriously.

B Experiment

Many searches for charmed particles were harder than people thought. Sometimes they were aided by sheer instrumental “overkill,” as in the case of the superb mass resolution attained in the experiment which discovered the $J$ particle. Sometimes the choice of a fortunate channel also helped, as in the production of the $\psi$ by $e^+e^-$ collisions with carefully controlled beam energies, or in the choice of the $e^+e^-$ decay mode in which to observe the $J$. Advances in instrumentation proved crucial, whether in the use of particle identification to pull out the initial $D^0$ signal from background or the study of charmed particles in high-background environments using vertex detection.

C Future searches

I do not see as clear a path in future searches as there was toward charm. In the case of supersymmetry, for example, the landscape looks very different. There is a wide variety of predictions, and one is looking for the whole supersymmetric system at once. Alternate schemes for solving the problems addressed by supersymmetry (e.g., dynamical electroweak symmetry breaking) are not yet even formulated in a self-consistent manner. Perhaps that makes the searches for physics beyond the standard model, which will be addressed in future experiments here at Fermilab and elsewhere, even more exciting.

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