THE SEARCH FOR CHARM
MY RECOLLECTIONS*

• A brief pre-history
• The charmed quark mass
• Gaillard, Lee & Rosner
• The November revolution
• The interim: where is open charm?
• Charm is found

*A detailed, carefully referenced, account of these developments can be found in

Jon Rosner, The Arrival of Charm

The Interplay of Theory and Experiment

Low Energy Data

Spectroscopy, V-A, $\Delta S = \Delta Q, \ldots \implies$ quark model

\[ \sim G_F^2 \Lambda^2 \implies \sim G_F^2 m_W^2 \sim g^2 / m_W^2 \]

Full renormalizability $\implies$ GWS

Meanwhile

soft pion theorems $\implies$ chiral symmetry

scaling in $e^+e^-$, DIS $\implies$ asymptotic freedom

\{ \implies QCD \]
Flashback: Spectroscopy Before Gauge Theories

Many (integrally charged) 4-constituent models

Bjorken & Glashow 1964

- Coined the word charm: new Q-no

- Noted flavor conserving neutral current

"The baryon current us thus $\bar{\psi}\gamma_\mu(1 - \gamma_5)W\psi$, with the 4 by 4 matrix $W$ given by

$$W = \begin{pmatrix}
0 & 0 & \sin \theta & \cos \theta \\
0 & 0 & \cos \theta & -\sin \theta \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}$$

The relation $[W, W^+] = 2Q - 1$, independent independent of $\theta$, suggests a possible intimate connection between weak and electromagnetic interactions."
**Strangeness Changing Neutral Currents**

\[ \mu^- \xrightarrow{s} \bar{u} + \nu \xrightarrow{u} \mu^+ \bar{d} \quad \Rightarrow \quad \mu^- \xrightarrow{s} \bar{u} + \nu \xrightarrow{u} \mu^+ \bar{d} \]

Mohapatra, Subbba & Marshak 1968 also \( \Delta m_K \)

**GIM 1970:**
- \( u, c \) CANCELLATION: \( \Lambda \rightarrow m_c \)
- **IF** \( W^\pm \rightarrow W^\pm, W^0 \) NEUTRAL CURRENT CONSERVES FLAVOR

**BIM 1972:** Anomaly cancellation

\[ \sim G_F^2 \Lambda^2 \left( \frac{1}{16\pi^2} \right) \quad \Lambda \sim \text{a few GeV}(4\pi) \]
The Mass of the Charmed Quark

Rare K-decays in GWS/GIM

$K_L \rightarrow \gamma \gamma :$ 

$K_L \rightarrow \mu^+ \mu^- :$

$m_u^2 \ll m_c^2 \ll m_W^2 :$ 

$m_c \approx \begin{cases} 
1.5 \text{GeV} & \text{no QCD} \\
2 \text{GeV} & \text{QCD $\sqrt{\propto}$ color factors $\times$} 
\end{cases}$
Historical notes

- AI Vainstein & IB Khriplovich 1973: \( K_L \to \mu^+\mu^- \), \( \Delta m_K : \Delta m \sim 1 \text{ GeV} \)
  
  Ma 1974 \( K \to 2\mu, 2\gamma \): \( m_c \approx 5\text{GeV} \)

- \( K_L \to \mu^+\mu^- \):

\[
\begin{array}{c}
\begin{array}{c}
\text{cancellation: } a = 0 \implies \text{weak bound on } \Delta m^2
\end{array}
\end{array}
\]

\[ \begin{aligned}
&\begin{array}{c}
\begin{array}{c}
\Delta m^2 \propto \frac{m^2_c - m^2_u}{m^2_W} \left[ a \ln \left( \frac{m_W}{m_c} \right) + b \right]
\end{array}
\end{array}
\end{aligned}\]

GL found also \( b = 0 \): symmetry? \( \epsilon^{\mu\nu\rho\sigma} \to -\epsilon^{\mu\nu\rho\sigma} \) GL & Shrock

\[ \begin{aligned}
&\begin{array}{c}
\begin{array}{c}
\text{GL found also } b = 0 : \text{ symmetry? } \epsilon^{\mu\nu\rho\sigma} \to -\epsilon^{\mu\nu\rho\sigma}
\end{array}
\end{array}
\end{aligned}\]
• GL Abstract:

To explain the small $K_L-K_S$ mass difference and nonsuppression of $K_L \rightarrow \gamma\gamma$, it is found necessary to assume $m_P/m_{P'} << 1$, where $m_P$ is the mass of the proton quark and $m_{P'}$, the mass of the charmed quark, and $m_{P'} < 5$ GeV.

Text:

Equation (2.8) is compatible with either with $m_{P'} \simeq m_P$ and large, and $m_{P'} - m_P \simeq 1$ GeV, or $m_P \ll m_{P'}$ and $m_{P'} \simeq 1.5$ GeV.

MS version 1: $1.5 \rightarrow 2$ (J-M G) $2 \rightarrow 1.5$

Appendix:

$K_L \leftrightarrow K_S$:

\[ \begin{array}{c}
\text{---} \quad \text{---} \\
\text{---} \quad \text{---}
\end{array} \quad + \quad \begin{array}{c}
\text{---} \\
\text{---} \\
\text{---}
\end{array} \quad \Rightarrow \quad 1.5 \rightarrow 2
\]

(London July 1974: 1.5)
Our discussion is largely based on intuition gained from the familiar, but not necessarily understood, phenomenology of known hadrons, and predictions must be interpreted only as guidelines for experimenters.

- $SU(3)_F \rightarrow SU(4)_F$  linear vs quadratic mass sum rules? $m(^3S_1) < 2m_D$

- Zweig rule $\rightarrow$ narrow $^3S_1$: $\Gamma \approx 2$ MeV

- weak coupling selection rules:
  \begin{align*}
  \Delta C &= \Delta Q = +1 \quad \text{production} \\
  \Delta C &= \Delta S = -1 \quad \text{decay}
  \end{align*}

- signal for $\nu \rightarrow \text{charm}$

- chiral symmetry wrong $F_\pi = \sqrt{2}f_\pi$!

- parton model for DIS

L Quigg & R, QR

GLR Conclusions: Look for

- **DIRECT LEPTON PRODUCTION**
- **LARGE NUMBERS OF STRANGE PARTICLES**
- **NARROW PEAKS IN MASS SPECTRA OF HADRONS**
- **APPARENT STRANGENESS VIOLATIONS** \((c \rightarrow s, \bar{c} \rightarrow d)\)
- **SHORT TRACKS, \ldots LIFETIME \sim 10^{-13} \text{ SEC}**
- **DI-LEPTON PRODUCTION IN NEUTRINO REACTIONS**
- **NARROW PEAKS IN \(e^+e^-\) OR \(\mu^+\mu^-\) SPECTRA**
- **TRANSIENT THRESHOLD PHENOMENA IN DI LEPTOPRODUCTION**
- **APPROACH OF \((e^+e^- \rightarrow \text{hadrons})/(e^+e^- \rightarrow \mu^+\mu^-)\) RATIO TO 3^{\frac{1}{3}}, \text{ PERHAPS FROM ABOVE}**
- **ANY OTHER PHENOMENA THAT MAY INDICATE A MASS SCALE OF 2-10 \text{ GeV}**
HINTS OF CHARM?

Abstract: **Muon pairs in the mass range** $1 < m_{\mu\mu} < 6.7$ GeV/c$^2$ **have been observed**
... **the cross section** ... **exhibits no resonant structure.**

Text: **Indeed, in the mass region near 3.5 GeV/c$^2$, the observed spectrum may be reproduced by a composite of a resonance and a steeper continuum.**

Niu et al. 1971

$X \rightarrow \pi^0 + \pi^+$

$m_X = 1.78$ GeV

$\tau_X = 2.2 \times 10^{-14}$ sec
HINTS OF CHARM?

Rubbia for Aubert et al. London, July, 1974
\[ \nu + Z \rightarrow \mu + X \]

TWO EVENTS HAVE BEEN OBSERVED IN WHICH THERE IS AN APPARENT SIMULTANEOUS PRODUCTION OF TWO PENETRATING PARTICLES OF OPPOSITE SIGN (MUONS).

Litke et al. 1973
Tarnopolsky et al. 1973
Richter et al. 1974
\[ e^+ e^- \rightarrow \text{hadrons} \]
(from GLR)

FIG. 8. Data on the ratio \( R = \sigma(e\bar{e} \rightarrow \text{hadrons})/\sigma(e\bar{e} \rightarrow \mu\bar{\mu}) \), and predictions of the asymptotically free quark model without charm (lower curve) and with charm (upper curve). (a) CEA data: Litke et al., 1973. Tarnopolsky et al., 1973. (b) SLAC-LBL data: Richter, 1974. (c) This is taken from Adler, 1974.
November 1974

Aubert et al. \( p + Z \to ^3S_1 + X \) \hspace{2cm} Augustin et al. \( e^+ + e^- \to ^3S_1 \)

GLR Appendix: \( m(^3S_1) = 3.1 \text{ GeV}, \) decay widths, excited states \( \Rightarrow \)
more precise predictions for spectrum, couplings

Enter QCD

Zweig rule \( \Rightarrow \) asymptotic freedom \hspace{2cm} Appelquist & Politzer Dec 1974

\[ ^1S_0 : \propto g^2 \quad ^3S_1 : \propto g^3 \quad |\psi(0)| \propto g^3 \]
\[ \Gamma \simeq 0.6 \text{ MeV} \]

\( SU(4) \) mass sum rules \( \Rightarrow \) quarks in coulomb-like chromomagnetic field

Better predictions for fermion masses \hspace{2cm} De Rújula, Georgi & Glashow March 1975
Waiting for open charm: a view from Europe

**Color vs Charm (CERN): Ward (LRG) vs Ellis & Gaillard**

**CERN tower**

**Cargèse 1975: Where are P-wave charmonium states?**  
Rudaz

\[ R = \frac{\sigma(\text{hadrons})}{\sigma(\mu\mu)} \text{ too high} \quad \tau \text{ confusion!} \]

**Where is } D \rightarrow \bar{K} + \pi?**

GLR wrong \( f_\pi \)  
LQR, QR  
resonance production  
Einhorn & Q  
etc

**Counting K’s in } e^+e^- \rightarrow \text{hadrons}**

When will you stop believing in charm?  
CERN cafeteria
Charm is found

\[ \Delta S = -\Delta Q \text{ observed} \]

Cazzoli et al, March 1975

\[ \nu p \rightarrow \mu^- + (\Lambda\pi^+\pi^+\pi^-)_{2462 \text{ MeV}} \]

\[ e^+e^- \rightarrow D^\pm + X \text{ observed} \]

Goldhaber et al, June 1976

\[ e^+e^- \rightarrow (K\pi, K3\pi)_{1865 \text{ MeV}} + X \]

First P-state observed

Braunschweig et al, July 1975

\[ \psi'(3.7) \rightarrow \gamma + (\gamma J/\psi)_{3.52 \text{ GeV}} \]
IN MEMORIAM

Benjamin W. Lee 1935-1977

Bruce Winstein 1943-2011
Conclusions

Well, those were great days. The 1960s and 1970s were a time when experimentalists and theorists were really interested in what each other had to say, and made great discoveries through their mutual interchange. We have not seen such great days in elementary particle physics since that time, but I expect that we will see good times return again in a few years, with the beginning of a new generation of experiments at this laboratory.

The Making of the Standard Model
S. Weinberg

LET'S HOPE SO!
HAPPY RETIREMENT JON!