PHYSICS PROGRAM AT SPEAR ENERGIES

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Abstract

I present below a partial review of the physics program remaining to be completed over the SPEAR energy range along with examples of the running time needed for selected topics. The topics discussed are the following:

a. Meson spectroscopy from the ψ.
b. Details of production and decay for the η_c.
c. Charmed hadron spectroscopy.
d. Weak decays of D and F.
e. Mechanism of $e^+e^- \to q\bar{q} \to$ Hadron States.

I. Meson Spectroscopy from the ψ

The observation of at least two states, $\iota(1440)$ and $\theta(1640)$,[1] has demonstrated the importance of the ψ as a source for new mesons. Since in the framework of QCD $\psi \to \gamma gg$, the new states seen in conjunction with one photon are good candidates for states of gluonium. In the limit of small mixing with quark states one expects:[2,3]

1. A sequence of states with $J^{PC} = 0^{++}, 2^{++}, 0^{-+}, \ldots$; with the lightest having masses $\lesssim$ 2 GeV.
2. Decay characteristic of an SU(3) singlet. For example, before phase space corrections, one expects for the 2^{++} decay ratios: $\pi^0\pi^0:\pi^+\pi^-:K^+K^-:\eta\eta = 1:2:2:1$. Note, however, that the expectations may be different for the 0^{-+} because of helicity suppression in the decay.[3]
3. Widths somewhat smaller than in the case of quark states, although this is not true in all models.
4. Anomalously large production from the ψ.
5. No $q\bar{q}$ nonet into which the state fits.
6. Suppressed production from other initial state channels, particularly for example in $\gamma\gamma \to$ Mesons.

Note, the importance of information from other experiments in verifying (5) and (6).

For the two states that have been seen, the presently known information is summarized below.[1,4] In particular $\psi \to \gamma\iota$ is the largest $\gamma +$ light meson mode for the ψ, a fact which is difficult to explain without invoking the gluonium hypothesis.

	ι	Θ
m	$1440 \begin{smallmatrix}+20\\-30\end{smallmatrix}$	1640 ± 50
Γ	$70 \begin{smallmatrix}+20\\-30\end{smallmatrix}$	$220 \begin{smallmatrix}+100\\-70\end{smallmatrix}$
Rate	$B(\psi \to \gamma\iota)B(\iota \to K\bar{K}\pi)$ $= 4 \pm .7 \pm 1.0 \times 10^{-3}$	$B(\psi \to \gamma\Theta)B(\Theta \to \eta\eta)$ $= 4.9 \pm 1.4 \pm 1.0 \times 10^{-4}$
		$B(\psi \to \gamma\Theta)B(\Theta \to K^+K^-)$ $= 6.0 \pm .9 \pm 2.5 \times 10^{-4}$

Note: The lower limits from the observed modes, $B(\psi \to \gamma\iota) = 4 \times 10^{-3}$ and $B(\psi \to \gamma\theta) = 1.1 \times 10^{-3}$ are comparable to $B(\psi \to \gamma\eta') = 2.5 \times 10^{-3}$ and $B(\psi \to \gamma f) = 1.5 \times 10^{-3}$ which involve normal quark states of the same spin.

From the numbers above, branching ratios into interesting modes x efficiencies are $\simeq 10^{-4}$. A 1-year physics run (20 weeks) at the ψ at SPEAR would give $\simeq 5 \times 10^6$ events or $\simeq$ 500 events/interesting channel. This would allow a search for resonances perhaps down to the 10^{-5} level as well as a careful partial wave analysis for the more prominent modes. Stringent limits for a 0^{++} gluonium candidate would be of particular interest.

II. Properties of η_c

The η_c, in conjunction with the ψ, provides a good place to test QCD at intermediate energies, since: $\psi \to e^+e^-$, $\psi \to ggg \to$ Hadrons, $\eta_c \to \gamma\gamma$, $\eta_c \to gg \to$ Hadrons, $\psi \to \gamma\eta_c$ are all predicted in terms of α, α_s, the quark charges, and the wave function squared at the origin in the nonrelativistic limit.[4]

For example:

$$\frac{\Gamma(\psi \to e^+e^-)}{\Gamma(\psi \to ggg \to \text{Hadrons})} \simeq \frac{1}{10} \text{ implies } \alpha_s = .19.$$

Using this value we get:

$$\Gamma(\eta_c \to \text{Hadrons}) = \frac{27\pi}{5(\pi^2-9)\alpha_s}\,\Gamma(\psi \to \text{Hadrons}) = 7 \text{ MeV}.$$

As another example:

$\dfrac{\Gamma(\eta_c \to \gamma\gamma)}{\Gamma(\psi \to e^+e^-)}$ can be calculated in terms of the quark charges and gives a prediction $\Gamma(\eta_c \to \gamma\gamma) = 9$ KeV which is unfortunately too small to measure at SPEAR given the full width above.

Finally:

$\Gamma(\psi \to \gamma\eta_c)$ is an M1 transition which can be predicted from the ψ-η_c mass difference and should = 2.4 KeV which would imply an ~ 4% branching ratio

$$\frac{\Gamma(\psi \to \gamma\eta_c)}{\Gamma(\psi \to \text{All})}.$$

The presently measured numbers from the crystal ball experiment[6] are:

$$M_{\eta_c} = 2984 \pm 4 \text{ MeV}.$$

$$\Gamma_{\eta_c} = 12.4 \pm 4.1 \text{ MeV}.$$

$$B(\psi' \to \gamma\eta_c) = .28 \pm .08\%.$$

$$B(\psi \to \gamma\eta_c) = 1.13 \pm .33\%.$$

The last number is difficult to reconcile with the 4% expectation mentioned above.

Several decay modes for the η_c have been seen, all based on a few events and with ~ few per cent branching ratio. These final states are: $K^\pm K_s^0 \pi^\mp$, 4π, $2\pi 2K$, $\eta\pi^+\pi^-$, and $p\bar{p}$. For typical states the branching ratio into $\gamma\eta_c$ x branching ratio of η_c into a given state x detection efficiency $\simeq 10^{-5}$. Thus it would take ~ 10×10^6 ψ events in a general purpose detector, with good low energy photon efficiency, to get ~ hundreds of exclusive events per mode to examine. This would allow checks that the η_c is indeed an SU(3) singlet and perhaps allow examination of how $\eta_c \to gg$ turns into hadrons.

III. Charmed Hadron Spectroscopy

The mass splitting among charmed hadrons provides an interesting test of the spin and mass dependence of the quark-quark interaction. Considering the lightest mesons and baryons (with angular momentum = 0 for the constituent quarks), the simplest approximation to the masses is the sum of the constituent quark masses plus a spin dependent term which is:

$$\frac{\Delta_1 \langle \vec{S}_1 \cdot \vec{S}_2 \rangle}{m_1 m_2}$$

for mesons. Here m_1, m_2 are the constituent quark masses, $\langle \vec{S}_1 \cdot \vec{S}_2 \rangle$ is the expectation for the spins and Δ_1 is a phenomenological constant. For baryons the analogous term is:

$$\Delta_2 \left[\frac{\langle \vec{S}_1 \cdot \vec{S}_2}{m_1 m_2} + \frac{\vec{S}_1 \cdot \vec{S}_2}{m_1 m_3} + \frac{\vec{S}_2 \cdot \vec{S}_3 \rangle}{m_2 m_3} \right].$$

In the above we expect for the quark masses: $m_{u,d} \simeq$ 336 MeV, $m_s \simeq 509$ MeV (based on baryon magnetic moments) and $m_c \simeq 1500$ MeV. Fitting the familiar charm = 0, $J^P = 0^-, 1^-, 1/2^+, 3/2^+$ meson and baryon masses gives:

$$\Delta_1 \simeq 602\ m_u^2,\ \Delta_2 \simeq 196\ m_u^2\ ,$$

where m_u is given above. These formulas in fact give a good description of the spin dependent mass splittings.

If we use these formulas for the charm case we get the prediction:

$$m_{D^*} - m_D \simeq 135 \text{ MeV}$$

which agrees with the measured value. We can then predict:

$$m_{F^*} - m_F = \left(\frac{m_u}{m_s}\right)\left(m_{D^*} - m_D\right) \simeq 90 \text{ MeV},$$

which would imply that F* decays electromagnetically.

The lightest baryons are gotten by replacing an s by a c quark in the octet and decuplet states with unit strangeness, giving:

$$\Lambda_c^+$$

$$\underbrace{\Sigma_c^0,\ \Sigma_c^+,\ \Sigma_c^{++}}_{\text{spin } 1/2} \qquad \underbrace{\Sigma_c^{*0},\ \Sigma_c^{*+},\ \Sigma_c^{*++}}_{\text{spin } 3/2}$$

Using the mass formula above gives the following predictions, which can be compared to the case of the strange baryons:

Strange	Charmed
$m_{\Sigma^*} - m_\Sigma = 190$ MeV	$m_{\Sigma_c^*} - m_{\Sigma_c} = 65$ MeV
$m_\Sigma - m_\Lambda = 76$ MeV	$m_{\Sigma_c} - m_{\Lambda_c} = 157$ MeV.

These baryon masses predict a different decay pattern for the charmed baryons than for the strange baryons.

For Strange	For Charm
$\Sigma^* \to \Sigma\pi$ and $\Lambda\pi$	$\Sigma_c^* \to \Lambda_c\pi$
$\Sigma^\pm \to$ decay weakly	$\Sigma_c \to \Lambda_c\pi$
$\Sigma^0 \to \gamma\Lambda^0$	

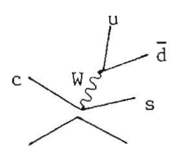
Only the Λ_c decays weakly. Note, this pattern is very sensitive to whether $m_{\Sigma_c} - m_{\Lambda_c}$ is larger or smaller than m_π.

The detection of the F, F*, Σ_c, Σ^*_c at SPEAR still remains to be accomplished. The F has appeared in various emulsion experiments and photoproduction at approximately the expected mass $\simeq$ 2050 MeV.

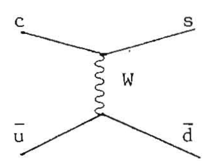
Beyond the lightest, L = 0, charmed particles, there should be a whole spectrum of excited states with $J^P = 1^+, 2^+, \ldots$. These should have more complicated splittings, depending now on the orbital angular momentum as well as the spin couplings, and could lead to more insight into the quark-quark forces. The cross sections for production of such states is not known; a good place to search might be $\simeq$ 6 GeV center of mass energy in e^+e^-. The states would show up in invariant mass plots, for example in $(D\pi)$ or $(D^*\pi)$ channels.

IV. Weak Decays of D and F

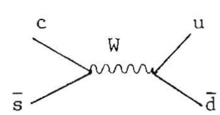
The study of charmed particle decay at SPEAR provides a second laboratory (with a larger variety of final states than in the strange case) for the study of the interplay of the weak and strong interactions. Some of the diagrams of interest that may contribute and some of their characteristics are as follows:[7]



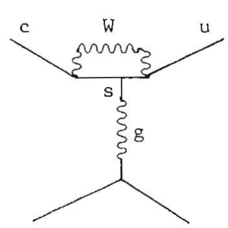
Light Quark Spectator diagram, contributes to D^0, D^+, F^+ decay.



W exchange diagram. Exists for D^0 only and leads to I = 1/2 final states only.



Annihilation diagram. Exists for F^+ only and leads to non-strange final states with I = 1.



Penguin diagram. Contributes to Cabibbo suppressed decays only and may enhance these.

A one year physics run (20 weeks) at SPEAR will yield about 10^5 D^+D^- and $D^0\bar{D}^0$ events. These should allow reconstruction of about 10^4 D^0 and D^+ decays. The table below indicates the number of reconstructed D's one expects in the MARK III detector based on the MARK II branching ratios (which have large errors) and including the MARK III detection efficiency. The semi-leptonic values assume a 15% and 5% semileptonic brahcning ratio for the D^+ and D^0, respectively, and that only tagged events are used.

Mode	Reconstructed Events
$D^0 \to K^-\pi^+$	3,950
$K_s^0\pi^0$	750
$K^-\pi^+\pi^0$	5,100
$K_s^0\pi^+\pi^-$	1,650
K^-K^+	390
$\pi^-\pi^+$	150
$K^-e^+\nu$	280
$K^-\mu^+\nu$	120
$\pi^-e^+\nu$	18
$D^+ \to K_s^0\pi^+$	1,100
$K^-\pi^+\pi^+$	6,500
$K_s^0\pi^+\pi^0$	2,450
$\pi^-\pi^+\pi^+$	415
$K_s^0e^+\nu$	300
$K_s^0\mu^+\nu$	120
$\pi^0e^+\nu$	24

Several physics problems of particular interest are:

1. The lifetime ratio, $\tau(D^+)/\tau(D^0)$. This value has changed with time as experiments have improved and is most probably between 2 and 4. Dominance of the light quark spectator diagram, which was expected in the standard model, would imply a value close to 1.

2. The isospin content of various hadronic final states. It is indicative of the underlying decay mechanism: for example, the light-quark spectator diagram leads to I = 1/2, 3/2 final states, while the W exchange diagram, which exists for the D^0 only, leads to I = 1/2. Pairs of final states related by isospin which can be conveniently measured are:

$$D^0 \to K^-\pi^+ \text{ and } \bar{K}^0\pi^0,$$
$$K^-\rho^+ \text{ and } \bar{K}^0\rho^0,$$
$$\bar{K}^*\pi^+ \text{ and } \bar{K}^{0*}\pi^0.$$

3. A comparison of various Cabibbo-suppressed modes. These are sensitive to the Cabibbo angle for the charmed quark decay as well as the contribution of various diagrams, such as the "penguin diagram", which has been conjectured to be the basis of the $\Delta I = 1/2$ rule in strangeness changing weak hadronic decays. Examples include the decays

$$D^0 \to K^-\pi^+;\ K^-K^+,\ \pi^-\pi^+,$$
$$D^+ \to \bar{K}^0\pi^+;\ \bar{K}^0K^+,\ \pi^0\pi^+,$$
$$D^+ \to K^-\pi^+\pi^+;\ \pi^-\pi^+\pi^+.$$

4. A study of semi-leptonic decays. This includes a measurement of the semi-leptonic branching ratios for the D^0 and D^+, form factors for the $Ke\nu$ final state, the ratios of the $Ke\nu$ to $K\pi e\nu$ and $Ke\nu$ to $\pi e\nu$ widths. The latter is particularly important, since it provides a nearly model-independent measurement of the Cabibbo angle characterizing the charmed quark decay.

5. Although it is expected that D^0, $\bar{D}^0$ mixing effects and CP violation are small, it is important to check for these since an anomalously large effect would point to deficiencies in the standard model. In general, the strong eigenstates D^0 and $\bar{D}^0$ will mix, as for K^0 and $\bar{K}^0$, to give states with well defined decay lifetimes, D_S^0 and D_L^0. These are gotten by diagonalizing the mixing matrix:

$$\begin{bmatrix} m_{11} - \frac{i\Gamma_{11}}{2} & m_{12} - \frac{i\Gamma_{12}}{2} \\ m_{21} - \frac{i\Gamma_{21}}{2} & m_{22} - \frac{i\Gamma_{22}}{2} \end{bmatrix}$$

where to lowest order

$$m_{ij} - \frac{i\Gamma_{ij}}{2} = \sum_n \frac{\langle D_i|H_w|n\rangle\langle n|H_w|D_j\rangle}{m_{D^0} - E_n + i\varepsilon} .$$

Here i = 1 is D^0 and j = 2 is $\bar{D}^0$. The off-diagonal elements $\neq 0$ implies mixing and a non-symmetric matrix implies CP violation. For no CP violation $\Delta m = 2m_{12}$, $\Delta\Gamma = \Gamma_S - \Gamma_L = \Gamma_{12}$, and the eigenstates are $\frac{D^0 \pm \bar{D}^0}{\sqrt{2}}$.

The off-diagonal elements in the matrix come from states which D^0 and $\bar{D}^0$ decay to in common, for example multi-pion final states. These common modes are Cabibbo suppressed so that the ratio of off-diagonal/diagonal elements $\simeq \sin^2\theta_c$. This implies that $\Gamma_S \simeq \Gamma_L$ and there is little observable mixing if we start with a D^0 or $\bar{D}^0$. If all D^0 and $\bar{D}^0$ decay before we see them, we can define the effect of mixing experimentally by the ratio of rates for final states which seem to come from D^0D^0, $\bar{D}^0\bar{D}^0$ versus $D^0\bar{D}^0$:

$$r = \frac{N_{11} + N_{22}}{N_{12}} .$$

Here final states are associated with a particular D via for example the lepton charge for semi-leptonic decays or the charge of the K for Cabibbo allowed decays.

In terms of the elements in the mixing matrix:

$$r = \frac{2\rho}{1 + \rho^2} ,$$

where

$$\rho = \frac{4\left(\frac{\Delta m}{\Gamma}\right)^2 + \left(\frac{\Delta\Gamma}{\Gamma}\right)^2}{2 + 4\left(\frac{\Delta m}{\Gamma}\right)^2 - \left(\frac{\Delta\Gamma}{\Gamma}\right)^2}$$

With Cabibbo suppression of common D^0, $\bar{D}^0$ modes, $\rho \sim \sin^4\theta_c$ should be $\sim 10^{-3}$. With 10^5 $D^0\bar{D}^0$ events, using $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$ modes for the D^0 and the charge conjugate modes for the $\bar{D}^0$, the MARK III detector should be able to fully reconstruct ~ 250 $D^0\bar{D}^0$ events. Thus with the expected mixing numbers from the standard model it is unlikely that a clear mixing signal will be seen among the reconstructable events, although the number of events available would be getting close to what is needed for a measurement.

CP violation can be defined experimentally by $\frac{N_{11} - N_{22}}{N_{11} + N_{22}} = 0$. Since this number is expected to be small (perhaps $\sim \varepsilon = 2 \times 10^{-3}$) and $N_{11} + N_{22}$ is already small relative to N_{12}, CP violation for charm should be unobservable by several orders of magnitude for the standard model.

The weak decays of the F meson should allow further checks of whatever picture emerges from the D decay pattern. However, rates for F production at SPEAR are unknown and a best energy to accumulate F data is not established. We can however estimate F production rates by using the following:

1. The penalty for requiring a strange quark is between .2 to .5 based on data from high $p_\perp$ K^+/π^+ ratios and deep inelastic lepton scattering. To be specific we choose .3 below.
2. In the 4 GeV range at SPEAR $R \simeq 2$ for all of charm. This gives $\left[\frac{.3}{2.3}\right] \times 2 = .26$ units of R for F plus F* production.
3. For a year run at SPEAR in the 4 GeV range, we expect $\sim 10^5$ events per unit of R, which gives $\simeq 2.6 \times 10^4$ F plus F* events. For typical modes with branching ratio $\times$ efficiency $\simeq 10^{-2}$, we should get a few hundred reconstructable F's per mode.

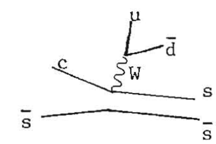
Although the arguments above are probably correct on average, both F and D (which produces background events) production are expected to vary strongly with energy in the 4 GeV resonance region. The discovery of an optimum place to run would therefore facilitate the F study both from the signal and background points of view.

Some of the important questions related to the F are as follows:

1. What is the semi-leptonic branching ratio, for example, is it more like the D^0 or the D^+. This would provide a constraint on enhancement mechanisms for the purely hadronic decay modes. The breakdown of the semi-leptonic modes into various contributions is also very interesting since the Cabibbo allowed final state is: $F^+ \to e^+\nu(s\bar{s})$, where the $(s\bar{s})$ can materialize into: η, η', or a gluonium state, if there is strong mixing between η' and any nearby glue-state. In general it would allow a check of the relative $(s\bar{s})$ content of the η' and η, if form factor corrections can be made, based on D decay data.

On the experimental end, the ability to look for these semi-leptonic decays will require the identification of a reliable channel by which $F\bar{F}$ production can be tagged.

2. For the hadronic F decays very little is known. For example, what is the likelihood of final states with pions only? Another interesting question is that of color suppression for the light-quark spectator diagram. From this diagram



final states can be of the type:

$$(u\bar{d})(s\bar{s}) \text{ or } (u\bar{s})(s\bar{d}).$$

However, because the W is colorless, the $(u\bar{s})(s\bar{d})$ combination will be a color singlet only 1/9 the time, so that $(u\bar{d})(s\bar{s})$ should be favored. A concrete prediction would therefore be that the rate for $\pi^+\eta^0$ is $\gg$ $K^+\bar{K}^0$ rate. From the case of the D meson branching ratios we can expect $\sim$ few percent of the F decays to go into these two final states.

3. Another decay of interest, which is large only for the F, is the purely leptonic decay:

$$F^+ \to \tau^+\nu_\tau .$$

This is described in terms of the decay constant f_F, analogous to f_π, and should occur with a few per cent branching ratio. As in the case of semi-leptonic decay, a reliable tagging channel is essential for seeing this mode.

V. Mechanism of $e^+e^- \to q\bar{q} \to$ Hadron States

The mechanism by which quarks yield hadrons is still poorly understood. At high energies, there is a phenomenological description in terms of quark fragmentation functions. Near charmed threshold, production of specific states is very complicated as both discrete $(c\bar{c})$ charmonium states and open explicit charm final states interact with each other in a complicated fashion. We list below a few of the measurements that would be interesting:

1. Accurate measurement of R versus energy for center of mass energies from 3.9 to 4.8 GeV.
2. A measurement of how R is made of specific channels: DD, DD*, D*D*, etc., over the same energy range.
3. A measurement of how spin effects the cross section; namely, D*/D ratios over the resonance region and at higher energies, and a measurement of the D* helicity.

References

I have not made an exhaustive list of references but rather attempted to refer to recent reviews which contain the original references as well as detailed discussions of the physics involved.

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