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PHYSICS OVERVIEW OF THE FERMILAB LOW ENERGY ANTIPROTON FACILITY WORKSHOP

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Physics Overview of the Fermilab Low Energy Antiproton Facility Workshop

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Abstract

A physics overview is presented of the Fermilab workshop to consider a possible high flux, low energy antiproton facility that would use cooled antiprotons from the accumulator ring of the Tevatron collider.

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I. Introduction

My charge from the workshop organizers is to give an overview of the physics that could be done with a low energy antiproton facility at Fermilab, including a summary of the physics topics discussed at the workshop. John Peoples has kindly given me some of the time allotted to him on the program, for which I thank him. Even with the hour I now have this is a tall order, given the breadth of topics to discuss.

I have been told by the organizers that it is fair to dream of a $\bar{p}$ ring with a maximum momentum $p_{LAB} \sim 8$ GeV, that would be distinguished by two parameters: momentum resolution that might with electron cooling reach

$$\Delta p/p \sim 10^{-5} \tag{1.1}$$

and a flux of

$$5 \cdot 10^7 \text{antiprotons/sec.} \tag{1.2}$$

These parameters would certainly define a remarkable facility.

The flux would be sufficient for the next one or two generations of experiments in fields that are now statistics-limited, such as meson spectrocopy, charm and charmonium spectroscopy and dynamics, CP violation, and dynamical studies of exclusive QCD and nuclear physics. For instance in the search for the gluonic states that are among the most dramatic predictions of QCD, beautiful results have come from e^+e^- machines, most recently from the study of radiative ψ decay with the Mark III detector, but the six million ψ's accumulated with the Mark III do not yield enough events in the channels of interest to resolve most of the questions suggested by the data. With the proposed $\bar{p}$ facility we are limited chiefly by the rate at which we are able to take data and analyze it, though it must also be said that it will in some cases be harder to find the physics among the backgrounds.

The beam resolution, (1.1), is an even more remarkable parameter than the flux. Together with high flux it implies extraordinary sensitivity to narrow states, unmatched as far as I can see by any other imaginable facility. I will illustrate this with two examples. First, used as a ψ factory our facility might be able to answer some of the questions raised by the e^+e^- data. Second, with the assumed parameters the device could be sensitive to a light Higgs bosons (of the nonminimal two doublet model). Anyone who has grappled with the problem of searching for Higgs bosons knows them as the most elusive quarry of all particle physics, so this is a particularly impressive example. To be precise, I will argue that it could be possible to detect the $\xi(2230)$, a state that is narrow within the resolution of the Mark III, in $\bar{p}p \rightarrow \xi$ if it is a Higgs boson in a two doublet model – an interpretation that is not contradicted by any existing data. Under this hypothesis I cannot imagine any other way that the narrowness of the ξ could be demonstrated to the few keV level that is required.

Finally the beam energy of 8 GeV in the lab implies the ability to carry this high–flux, high–resolution program to $\sqrt{s} = 4$ GeV with fixed target or 16 GeV in collider mode. A substantial portion of the physics discussed at this meeting requires the ability to reach these higher energies.

The range of physics that could be studied with such a device is extremely broad. We have heard talks at this workshop on the following topics:

Cold antiprotons: descriptions were given of two experiments being developed for LEAR that would use $\bar{p}$'s cooled to $O(10)^{\circ}K$ or, in more familiar units, O(1) femto–TeV, in order to measure the antiproton gravitational and inertial masses.

Dynamics: Studies of the nuclear force and of exclusive QCD were described, requiring high $\bar{p}$ flux, the latter requiring in addition the larger beam energies that would be attainable.

Charmonium and Charm: detailed studies can be made of the widths and transition amplitudes of the narrow states below $\bar{D}D$ threshold. Though far more difficult, it may also be possible to study the spectrum above $\bar{D}D$ threshold and especially the charmed baryons of which only one example is presently known.

CP and Other Discrete Symmetries: a first generation experiment approved for LEAR intends to study K^0 decays at the critical $O(10^{-3})$ level of sensitivity for ϵ'/ϵ, bringing to the field systematic uncertainties which differ markedly from those of the classical regeneration experiments. $K \rightarrow 3\pi$ and CPT invariance can be studied at levels far beyond what is possible for the regeneration experiments. We also heard from Donoghue of a new proposal to search for milli–weak CP violations in hyperon pair production, $\bar{p}p \rightarrow \bar{\Lambda}\Lambda, \bar{\Xi}\Xi, \cdots$. This proposal requires the very high fluxes of our hypothetical facility

than is possible under the present monopolistic regime of the K^0 meson.

Meson Spectrum $-q\bar{q}, gg, \bar{q}qg, \bar{q}\bar{q}qq$: This is a good place to acknowledge the contribution of I. Singer to the workshop, who emphasized the importance of the extra term $[A_\mu, A_\nu]$ in the QCD curvature tensor

$$F^{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + [A_\mu A_\nu]. \tag{1.3}$$

The most palpable manifestations of that term are the gg glueballs and $\bar{q}qg$ meiktons (known in other quarters as hermaphrodites or hybrids) that have not yet been definitively identified. The rate of progess has been constrained primarily by statistical limitations. Major contributions can be made since the available $\bar{p}$ flux means that enormous statistical samples are possible, limited perhaps as much as anything else by off–line analysis capability.

Plan of this talk: in the next section I will present two examples that illustrate the power of such a facility to produce narrow states at high rates. In the third section I will review the various physics topics that have been discussed at the meeting. The concluding section contains a brief summary of the advantages and disadvantages of the proposed facility.

II. Narrow States: ψ Factory and Higgs Formation

Consider first ψ production with our hypothetical facility. The smearing of the center of mass energy W due to the resolution of the beam momentum is

$$\Delta W = \frac{m_N p_{LAB}}{W E_{LAB}} \Delta p_{LAB}. \tag{2.1}$$

With the assumed $\Delta p_{LAB}/p_{LAB} \sim 10^{-5}$, the resolution at the ψ is

$$\Delta W \sim 12 \text{ keV} < \Gamma_\psi = 63 \text{ keV} \tag{2.2}$$

where I have neglected any further smearing due to the target – a small effect for a gas jet target which I will assume. The cross section is then undiminished by the beam spread and we find

$$\sigma(\bar{p}p \to \psi) = \frac{12\pi}{m_\psi^2 - 4m_N^2} B(\psi \to \bar{p}p) \sim 5\mu b. \tag{2.3}$$

using the experimental value $B(\psi \to \bar{p}p) \sim 2 \cdot 10^{-3}$. If we assume $\mathcal{L} = 10^{31}\text{cm.}^{-2}\text{sec.}^{-1}$, as expected for instance for the gas jet experiment E760, now being installed in the accumulator ring, then we obtain a phenomenal ψ yield:

$$N_\psi \sim 5 \cdot 10^8 \text{ for } T \sim 10^7\text{sec.} \tag{2.4}$$

This is 250 times larger than the number of ψ's produced in all e^+e^- experiments to date.

It's worth stopping a moment to compare $e^+e^- \to \psi$ and $\bar{p}p \to \psi$. The e^+e^- cross section is favored by $B(\psi \to e^+e^-)/B(\psi \to \bar{p}p) \sim 35$, but this is more than compensated by the loss due to the beam spread, which at SPEAR is $\Delta W/\Gamma_\psi \sim 70$ (I may have a $\sqrt{2}$ loose in this estimate). The rest of the difference is the luminosity, which for SPEAR at the ψ has ranged from 10^{29} to $\sim 4 \cdot 10^{29}$ compared to the 10^{31} certainly attainable with a gas jet. Of course the e^+e^- machine has the advantage of virtually zero non-resonant background, whereas in $\bar{p}p$ experiments we either need a clean tag, e.g., $\bar{p}p \to \chi \to \gamma\psi \to \gamma e^+e^-$, or superb background rejection as discussed in the first example below.

At $W = m_\psi$ the total $\bar{p}p$ cross section is $\sim 50\ mb$, which is 10^4 times the ψ production cross section and corresponds to a 1/2 megaherz rate into the detector – the order of magnitude that the next generation of LEAR experiments are being prepared to cope

with. It is clear from the size of the background that we can kiss the bulk of hadronic ψ decays goodbye. However some of the most fruitful studies have been in the radiative channel, $\psi \to \gamma X$, the glueball channel par-excellence since perturbatively it is $\psi \to \gamma gg$ with the digluon in a color singlet. We may be able to study certain decays in this channel.

As a specific example consider the $\xi(2230)$, discovered[1] in $\psi \to \gamma\xi$, $\xi \to K^+K^-/K_SK_S$. The ξ is especially interesting because it is narrow within the resolution of the Mark III, $\Gamma_\xi \sim 20 \pm 20$ MeV. Its spin is unknown because the branching ratio $B(\psi \to \gamma\xi) \cdot B(\xi \to \bar{K}K) \sim 10^{-4}$ is so small that the 6,000,000 ψ decays of the Mark III data sample are insufficient after acceptances for a spin deterimination – an estimate at the Beijing workshop was that 20,000,000 ψ's might be needed. Suggested interpretations are a high spin $\bar{s}q$ state, a $\bar{q}qg$ meikton, and a Higgs boson in a two doublet model. Could we use $\bar{p}p \to \psi \to \gamma\xi$ to determine its spin?

With the measured branching ratio[1] $B(\psi \to \gamma\xi) \cdot B(\xi \to K^+K^-) \sim 3 \cdot 10^{-5}$ a sample of $4 \cdot 10^8$ ψ's corresponds to $\sim 1\frac{1}{2} \cdot 10^4$ events in $\bar{p}p \to \psi \to \gamma\xi \to \gamma K^+K^-$. The problem is the continuum backgrounds from $\bar{p}p \to K^+K^-\gamma$ and especially $\bar{p}p \to K^+K^-\pi^0$. The former is not a serious problem: at $W = 2.93$ GeV, the upper limit[2] $\sigma(\bar{p}p \to K^+K^-) < 2\mu b$ implies $\sigma(\bar{p}p \to K^+K^-\gamma) \lesssim \frac{\alpha}{\pi} \cdot 2\mu b$ or $\lesssim 5 \cdot 10^5$ events for the assumed integrated luminosity. For photon energies corresponding to $\psi \to \gamma\xi$ this source of background should be well below the signal.

The serious background is from $\bar{p}p \to K^+K^-\pi^0$, for which I have not been able to find a measurement near $\sqrt{s} = m_\psi$. From a compilation of measurements (figure 1 of ref. 3) I find $\sigma(\bar{p}p \to K_SK^\pm\pi^\mp) \sim 5\mu b$ from which I guess that $\sigma(\bar{p}p \to K^+K^-\pi^0) \sim 2\mu b$ (e.g., for $\bar{K}K\pi$ in the I = 0 channel, $K_SK^\pm\pi^\pm$: $K^+K^-\pi^0 = 2 : 1$). If the background events have an approximately flat distribution in K^+K^- mass and $m(K^+K^-)$ can be measured to 10 MeV, then the background is $\sim 10^6$ $K^+K^-\pi^0$ events in the bin with a signal of $\sim 1\frac{1}{2} \cdot 10^4$ $K^+K^-\gamma$ events. The E760 experiment now going into the accumulator ring expects to be able to reject all but 10^{-3} of the nonforward $\bar{p}p \to \pi^0\pi^0$ background against the $\bar{p}p \to \eta_c \to \gamma\gamma$ signal, implying 97% rejection for single π^0's.[4] At that level the surviving background against $\psi \to K^+K^-\gamma$ would be $3 \cdot 10^4$ $K^+K^-\pi^0$ events or twice the $\psi \to \xi\gamma$ signal. Given the level of statistics and the ability to study the side bands in K^+K^- both on the ψ and by going off the ψ, there would be a good chance to measure the spin of

ξ. The real conclusion however from this crude set of guesses is that the experiment is close enough to being possible that a more careful and realistic analysis is worth doing. Two final comments: (1) $\xi \to K_S K_S$ should also be considered and (2) statistics are large enough that we can afford a 5% photon converter if it helps against the π^0 background.

As a second, more spectacular example I want to consider the possibility of forming $\xi(2230)$ directly, $\bar{p}p \to \xi \to \bar{K}K$, under the hypothesis that it is a Higgs boson.[5] This hypothesis is suggested by the fact that the Mark III has not been able to resolve the width of the ξ, and it would become truly compelling if we could establish that $\Gamma_\xi(TOT) \ll 1$ MeV. As far as I can see, this is only possible in a $\bar{p}p$ facility with the hypothesized $\Delta p/p$ of order 10^{-5}.

For the Higgs boson of the minimal standard model, we have[6]

$$\frac{\Gamma(\psi \to \gamma H_{\text{standard}})}{\Gamma(\psi \to e^+e^-)} \cong \frac{1}{2}\frac{G_F m_\psi^2}{4\sqrt{2}\alpha}\left(1 - \frac{m_H^2}{m_\psi^2}\right) \tag{2.5}$$

where the factor 1/2 is a QCD correction.[7] For $m_H = 2.23$ GeV this would give

$$B(\psi \to \gamma H_{\text{standard}}) = 1.5 \cdot 10^{-5}, \tag{2.6}$$

at least an order of magnitude less than the rate for $B(\psi \to \gamma\xi)$, since $B(\psi \to \gamma\xi \to \gamma\bar{K}K) \gtrsim 10^{-4}$. We therefore consider the hypothesis[8] that ξ is part of a two doublet model, which then necessarily has an enhanced coupling to the charmed quark. The two doublets $\Phi_1$andΦ_2 have vacuum expectation values v_1 and v_2 with $v_1^2 + v_2^2 = v^2 = (.25\text{TeV})^2$ in order to fit G_F or M_W. Such models have large flavor–changing neutral currents unless they are constrained,[9] the most natural constraint being to require Φ_1 to couple only to weak–isopin up fermions (only u, c, t if we neglect the possibility of neutrino masses) and Φ_2 to couple only to weak–isopin down fermions (d, s, b and e, μ, τ). We assume that ξ is predominantly the neutral real component of Φ_1, so that its coupling to the charmed quark is enhanced by v/v_1 in amplitude relative to the coupling of the standard Higgs boson.

So far only $\xi \to \bar{K}K$ has been observed, but simple counting suggests $B(\xi \to \bar{K}^*K^*) \sim 3B(\xi \to \bar{K}K)$. I will assume for the sake of having a definite scenario that $B(\xi \to \bar{K}K) \sim 1/5$ so that $B(\psi \to \gamma\xi) \sim 5 \cdot 10^{-4}$: this is not an important assumption since the final estimate of the yield will be independent of it. Then from eq. (2.6) we require an

enhancement factor

$$\frac{v}{v_1} = \sqrt{\frac{5 \cdot 10^{-4}}{1.5 \cdot 10^{-5}}} \sim 6 \tag{2.7}$$

In lowest order ξ can decay only by its $\bar{u}u$ coupling, but in fact its predominant decay is by c and t loops into two gluons:

$$\Gamma(\xi \to gg) = 6^2 \cdot (\frac{\alpha_s}{\pi})^2 \frac{\sqrt{2}G_F}{18\pi} m_\xi^3 \sim 1 \text{ keV} \tag{2.8}$$

This is just the result of ref. (6) enhanced by eq. (2.7).

Naively one would expect the two gluons to hadronize in a flavor symmetric way, so that the model appears to be already contradicted by the upper bound[1] $\Gamma(\xi \to \pi\pi) < 0.2\Gamma(\xi \to \bar{K}K)$. However the J = 0 amplitude $gg \to \bar{q}q$ is proportional to m_q so that $gg \to \bar{s}s$ is dominant (this is the only point in which I am going beyond the arguments of Barnett *et al.* and Wiley[8]), for essentially the same reason that $\Gamma(\pi \to \mu\nu) \gg \Gamma(\pi \to e\nu)$. This argument has been made[10] to explain the predominance of the $\bar{K}K\pi$ decays of the glueball candidate $\iota(1460)$, and seems to be supported by recent Mark III data showing strangeness enhancement of the η_c decays to two vector mesons, also via two gluons in the J = 0 channel. By construction ξ has no (or very small) couplings to b quarks and to muons, so the bounds on $\Upsilon \to \gamma\xi$ and $\xi \to \mu\bar{\mu}$ are both irrelevant.

Having completed this baroque but necessary introduction to the model, we can now consider the possibility of observing ξ in $\bar{p}p \to \xi \to \bar{K}K$. We estimate $B(\xi \to \bar{p}p)$ by comparison with the measured value for $B(\eta_c \to \bar{p}p) \sim 1 \cdot 10^{-3}$, since both decays occur by hadronization of two gluons in the J = 0 channel. A simple estimate based on the QCD counting rules corrected by phase space (p–wave for ξ and s–wave for η_c) is

$$\begin{aligned} B(\xi \to \bar{p}p) &\sim \left(\frac{m_{\eta_c}}{m_\xi}\right)^{10} \cdot \frac{\beta_\xi^3}{\beta_{\eta_c}} \cdot B(\eta_c \to \bar{p}p) \\ &\sim 4 \cdot 10^{-3} \end{aligned} \tag{2.9}$$

The exponent in (2.9) is "10" rather than the more familiar "8" associated with the square of the proton form factor, because of precisely the same helicity argument invoked in the previous paragraph to explain the predominance of $\xi \to \bar{s}s$.

From (2.9) we obtain the cross section

$$\sigma(\bar{p}p \to \xi) \sim 13\mu b. \tag{2.10}$$

At $W = m_\xi$ the beam spread $\Delta p_{LAB}/p_{LAB} \sim 10^{-5}$ implies a resolution in W of only 5 keV(!), so that the observed cross section is only degraded by a factor ~ 5:

$$\bar{\sigma}(\bar{p}p \to \xi) = \sigma \frac{\Gamma_\xi}{\Delta W} \sim 3\mu b. \tag{2.11}$$

From the previous assumption that $B(\psi \to \gamma\xi) \sim 5 \cdot 10^{-4}$ we have $B(\xi \to K_S K_S) \sim .06$, so including $B(K_s \to \pi^+\pi^-)$ we have finally

$$\sigma(\bar{p}p \to \xi \to K_S K_S \to \pi^+\pi^-\pi^+\pi^-) \sim 80\text{nb}. \tag{2.12}$$

which is a large signal for our hypothetical facility. (Notice how the assumption for $B(\psi \to \gamma\xi)$ has cancelled: making $B(\psi \to \gamma\xi)$ larger we increase the enhancement factor v/v_1 and Γ_ξ, thereby increasing $\bar{\sigma}$, (2.11), but decreasing $B(\xi \to K_S K_S)$ and (2.12) by the same factor.)

Only two low statistics bubble chamber measurements[12] are available for $\bar{p}p \to K_S K_S$ in the ξ mass region. One experiment finds in a region just below the ξ, $W = 2.15 - 2.20$ GeV, that $\sigma(K_S K_S) \sim 4 \pm 2\mu b$ while the other, just above the ξ, $W = 2.26 - 2.41$ GeV, finds $1 \pm 1\mu b$. If I split the difference and guess at 2.5 μb, then the background to (2.12) is

$$\sigma(\bar{p}p \to K_S K_S \to \pi^+\pi^-\pi^+\pi^-) \sim 1.2\mu b \tag{2.13}$$

with large uncertainty. In this case we have statistics to burn: running for a modest $T \sim 10^6$ sec. at a modest $\mathcal{L} \sim 10^{30}\text{cm.}^{-2}\text{sec.}^{-1}$ (assuming an internal gas jet target) we have $8 \cdot 10^4$ events in our signal over a background of $1.2 \cdot 10^6$ with a statistical significance of 70 standard deviations. A more relevant consideration is that the cross section must be measured to about 5% accuracy. This should be possible since errors can be controlled by running off resonance.

Of course we still have to consider how we would find the ξ since the Mark III only gives us its mass to 10 or 20 MeV. This is also manageable but unlike the previous exercise uses both the high flux and the exquisite resolution of our gedanken machine. Assuming $\mathcal{L} = 10^{31}\text{cm.}^{-2}\text{sec.}^{1}$ and again $\Delta W = 5$ keV, the number of events in signal and background for a scan of t seconds is

$$N_{\text{Signal}} \sim 0.8 \ t \tag{2.14}$$

$$N_{\text{Background}} \sim 12 \ t \tag{2.15}$$

If we require an n standard deviation effect in the ξ bin then the time to scan 10 MeV in 5 keV steps is

$$T_{10\,\text{MeV}} \sim \frac{1}{2} n^2 \text{ days} \tag{2.16}$$

So 12 days of machine time would suffice for a scan with 5σ statistical sensitivity. This does not count the time it would take to twiddle the knobs 2000 times. If this can be automated at three minutes per twiddle, as has been discussed at this workshop in connection with plans for LEAR, then twiddling adds about 4 days to the 10 MeV scan.

The point of this example is of course not that $\xi(2230)$ is a Higgs boson (my money's riding on the meikton interpretation for now) but rather that it is a viable hypothesis that as far as I can see could only be directly verified with a facility of the kind we are discussing. Other experiments could refute the Higgs hypothesis, e.g., by establishing $J \neq 0$ or $\Gamma_\xi \sim O$ (MeV) or by producing ξ in the two photon channel,[13] but none that I can imagine has a chance to verify its narrowness at the $O(10)$ keV level. As such this discussion should be viewed as a specific, generic example of a class of important physics that could only be approached with a facility of the kind we are discussing.

III. Survey of Physics Topics

In this section I will review the physics topics discussed at the meeting. Taken together they represent a highly varied program with many prospects for important results. (I apologize to the previous speakers at this session, whose talks I'm not able to discuss because I was completing my own.)

A. Cold $\bar{p}$'s

Two experiments under development at LEAR were described to cool and hold $\bar{p}$'s in a Penning trap at temperatures of order $10^0 K$ or $10^{-3} eV$. The Seattle group (presentation by G. Gabrielse) has previously imprisoned electrons, positrons, and protons in order to make precise measurements of masses and magnetic moments. (One electron was held in solitary confinement for nine months; being a fermion, it probably suffered little.) As a first generation experiment they propose to measure the $\bar{p}$ mass with an accuracy of 10^{-9} by measuring the cyclotron frequency of the trapped $\bar{p}$ at the precision previously achieved with e^+ and p. A measurement at 10^{-9} would improve our knowledge of the antiproton mass by about four orders of magnitude.

The second collaboration, represented here by M. Hynes, intends to time the ascent of the cooled $\bar{p}$'s in a drift tube in order to measure the gravitational mass to an accuracy of order 1%. H^- ions would be used to control the tiny electromagnetic effects that plagued the Stanford drift tube experiment with positrons. This would be the first direct measurement of even the sign of the $\bar{p}$ gravitational mass. Some theoretical motivations were discussed by T. Goldman.

Both groups are thinking about the longer term future of cold $\bar{p}$'s including the possibility to develop polarized $\bar{p}$ sources and applications to atomic, condensed matter and solid state physics.

B. Nuclear Potential

In the isobar exchange representation of the nuclear potential, many properties of ordinary nuclei are a consequence of the cancellation in the central potential of the short range repulsive core (attributed to ω exchange) and an attractive force (the s-wave dipion or "σ" exchange). Antinucleons are an interesting probe of this notion since in the $\bar{N}N$ interaction both forces would be attractive, giving rise to qualitatively different physics.

The simplicity of this observation is however obscured by the additional contribution of annihilation channels to the potential, which for the central potential are known to be large.

Similar, dramatic affects are predicted for the spin–dependent terms in the potential as discussed by C. Dover. In the NN channel the spin–orbit and spin–spin forces benefit from constructive interferences and dominate, but for $\bar{N}N$ they should be small and the tensor force should dominate. High statistics experiments are needed with polarized targets and/or polarized beams. The largest effects are predicted for $\bar{p}p \to \bar{n}n$ which, given a polarized target, could also serve as a good source of polarized antineutrous.

As in the discussion of the central potential, the study of spin dependence is also obscured by the possibility of large contributions from the annihilation channels. One possibility is to try to use QCD to understand these effects. This would be a step beyond an existing program attempting to identify simple QCD mechanisms responsible for the pattern of enhancement and suppression observed in $\bar{p}p$ annihilation at rest into various final states (talks by Dover and Myhrer). This seems a difficult undertaking to particle physicists accustomed to regarding QCD at 1 fermi as too complex to yield to simple dynamical models. On the other hand we have our own useful though poorly understood selection rules (e.g., the Okubo–Iizuka–Zweig rule), and we should be open to the possibility that simple regularities might emerge form the data.

C. Exclusive QCD

QCD emerged from the study of inclusive cross sections at large momentum transfers, such as deep inelastic electron scattering. For the last few years perturbative QCD has also been used successfully to predict scaling laws for exclusive cross sections at large momentum.[14] Now we are at the beginning of another ambitious step, discussed by S. Brodsky, to use exclusive processes to study the spin and momentum dependence of hadronic wave functions, which are themselves due to nonperturbative QCD dynamics. In deep inelastic electron scattering we measure the nucleon structure functions which reflect the charge–weighted, longitudinal momentum distribution of the nucleon constituents summed over all Fock states, such as $qqq, qqqq\bar{q}, qqqg, \ldots$. In the exclusive processes we probe the momentum and spin dependence of the wave function corresponding just to the leading or valence Fock state configuration, with the higher Fock states making contributions that are suppressed by powers of the large momentum transfer.

Predictions are based both on theoretical models of the wave functions and on constraints obtained from measurements related by crossing symmetry. For example, at sufficiently large s and fixed center of mass angle Θ_{CM}, the counting rules imply the scaling law

$$\frac{d\sigma}{d\Omega}(\bar{p}p \rightarrow \gamma\gamma) = \frac{1}{p_T^{10}} f(\Theta_{CM}) \tag{3.1}$$

but have nothing to stay about the angular distribution, $f(\Theta_{CM})$. Predictions for $f(\Theta_{CM})$ are obtained by fitting theoretical models of the proton wave function to Compton scattering data, $\gamma p \rightarrow \gamma p$, at large momentum transfer. Similar studies can be carried out in other channels, such as $\bar{p}p \rightarrow \gamma M, MM, \bar{B}B$, where "M" stands for meson and "B" for baryon.

The minimum momentum transfer needed for the asymptotic behavior to set in is not precisely known and may vary from process to process. Recent data from $\gamma\gamma \rightarrow \bar{p}p$ shows that for $\bar{p}p \rightarrow \gamma\gamma$ asymptopia has not set in at $\sqrt{s} \sim 3$ GeV, and for processes with larger numbers of elementary constituents such as $\bar{p}p \rightarrow \gamma M, MM, \bar{B}B$, it may be even further delayed. This means that the full 16 GeV of energy available in collider mode might be needed to carry out these studies. Since at the higher energies the exclusive cross sections are greatly diminished, high $\bar{p}$ flux may also be a critical feature.

<u>CP Violation</u>

Jaffe, Landua, and Wolfenstein described the experiment to study K^0 decays that will run at LEAR in 1987. The experiment proposes to measure ϵ'/ϵ to a sensitivity of $2{\cdot}10^{-3}$, of the same order as current CERN and Fermilab experiments. This sensitivity is in the range needed to test the KM model of CP violations, which, despite considerable theoretical uncertainty from the QCD input to the calculations, is unlikely to be smaller than 10^{-3}. It complements the existing experiments because it does not share the systematic uncertainties due to K_S regeneration, though of course it has its own different systematics to contend with.

The experimental technique is to study the exclusive final states

$$\bar{p}p \rightarrow K^+\pi^-K^0 + K^-\pi^+\bar{K}^0. \tag{3.2}$$

The K^0 or $\bar{K}^0$ is tagged by detecting the K^+ or K^- and the decays of the neutral K to $\pi^+\pi^-$ and $\pi^0\pi^0$ are then measured as a function of the K^0 proper time from the interaction vertex. In addition to measuring η_{+-} and η_{00} well enough to give ϵ'/ϵ to $2{\cdot}10^{-3}$, this technique is also expected to measure the phase difference $|\phi_{+-} - \phi_{00}|$ to less than 2°. The current value is $14° \pm 7°$, though CPT invariance implies that it should be less than 0.1°.

By similarly measuring the $\pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$ decays as functions of the proper time, the experiment is expected to surpass the presently crude knowledge of η_{+-0} and η_{000} by three orders of magnitude. Measurement of the K^0 semileptonic decay modes allow sensitive tests of T invariance (and therefore of CPT) and of the $\Delta S = \Delta Q$ rule.

A new proposal to study CP violation was discussed by J. Donoghue that is particularly suited to a high flux $\bar{p}$ facility. The idea is to measure asymmetries in the decays of hyperon–antihyperon pairs, such as

$$\bar{p}p \rightarrow \bar{\Lambda}\Lambda \rightarrow \bar{p}\pi^+p\pi^-. \tag{3.3}$$

Since the $\bar{p}p$ initial state is a CP eigenstate, a nonvanishing final state expectation value for any CP odd observable indicates a violation of CP invariance. Consider for example the difference of scalar triple products

$$A = \vec{k} \cdot \left(\vec{q}(p) \times \vec{q}(\pi^-) - \vec{q}(\bar{p}) \times \vec{q}(\pi^+)\right) \tag{3.4}$$

where in the center of mass system $\vec{k}$ is the three–momentum of the initial state proton and $\vec{q}(X)$ is the three momentum of particle X in the final state. Under CP $\vec{q}(p) \times \vec{q}(\pi^-)$ is interchanged with $\vec{q}(\bar{p}) \times \vec{q}(\pi^+)$ so that $A \rightarrow -A$. Therefore a nonvanishing expectation value for A is a measure of CP violation.

Donoghue presented theoretical estimates for different CP violating effects in several different milli–weak models of CP violation. For instance, in the KM model the asymmetry in the parameter A, eq. (3.4), is of order 10^{-4}. For cascade pair production larger effects, of order 10^{-3}, are predicted, based on the expected hyperon polarization normal to the scattering plane.

To measure an asymmetry $A = (N_1 - N_2)/(N_1 + N_2)$ to n standard deviations, $(N_1 - N_2)/2 = n\left((N_1 + N_2)/2\right)^{1/2}$, we require an event sample of size $N_1 + N_2 = 2n^2/A^2$. For n = 5 and A = 10^{-4} we need $N_1 + N_2 = 5 \cdot 10^9$ events. The cross section[15] for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$

is $\sim 100\mu b$ for $p_{LAB} \sim 2 - 3GeV$, so that $\mathcal{L} = 10^{31}\text{cm.}^{-2}\text{sec.}^{-1}$ would yield $5{\cdot}10^9$ events in $5 \cdot 10^6$ sec. The efficiency of the Trigger and the capacity of off-line analysis are then critical in assessing the feasibility of this approach. For the spin dependent asymmetries of order 10^{-3}, smaller samples of order $5 \cdot 10^7$ events would yield 5σ effects in the KM model.

If these experiments are feasible and produce nonvanishing results, they would greatly enhance our ability to study the origins of CP violation beyond what is now possible with experiments restricted to K decays. By measuring the effects in different hyperon species it will be possible to study the underlying mechanism, as can be seen in the tables accompanying Donoghue's talk.

Charmionium and Open Charm

M. Olsson discussed theoretical issues and Menichetti described the $\bar{p}p$ formation of $\chi(3510)$ and $\chi(3555)$ at the ISR and the improved $E760$ experiment now being installed in the Fermilab accumulator ring. Very precise measurements can be made of the masses, widths and transition amplitudes of the narrow $\bar{c}c$ states, including the singlet P-state and the two D-states ($J^{PC} = 2^{--}, 2^{-+}$) expected to lie below the DD* threshold for Zweig-allowed decay. Data already available indicates that $\bar{c}c$ decay and transition amplitudes are characterized by large relativistic and strong interaction corrections. Precise data would challenge theorists to understand these corrections, beginning from the qualitatively (and in some instances quantitatively) successful zero'th order nonrelativistic model of charmonium. A program of this nature could lead eventually to an understanding of the dynamics of light hadrons, for which no credible zero'th order approximation of the dynamics is now available.

The study of narrow $\bar{c}c$ states is made feasible by the clean tag afforded in processes like $\bar{p}p \to \chi \to \gamma\psi \to \gamma e^+e^-$. It will be more difficult to study the $\bar{c}c$ and charmed mesons and baryons above $\bar{D}D$ threshold. Perhaps the leptons and missing energy (neutrinos) of the semileptonic decays could provide the basis of a useable trigger. (Another possibility, suggested by Bjorken, is to use a displaced vertex tag.)

There are many interesting questions to study above $\bar{D}D$ threshold. We would like to see more of the charmed baryon spectrum than the single example discovered so far, the $\Lambda_c(2280)$. A $\bar{p}p$ facility would produce a larger fraction of its charm in baryon channels than

any other production mode. It would also be interesting to find some of the non-vector meson states, since knowledge of their masses would clarify the interpretation of the three bumps seen in the vector channel at 4.03, 4.16, and 4.42 GeV. These resonances – putative 3S, 2D, and 4S levels – are sensitive to the potential in the interesting large distance regime, though their masses are also sensitive at the ~ 25 MeV level[16] to continuum mixing effects. As discussed by Sharpe in his talk, the spectrum above $\bar{D}D$ threshold is also the hunting ground for $\bar{c}cg$ charmonium meiktons.

To get a very crude idea of the possible yields above $\bar{D}D$ threshold, I have used the QCD counting rules to estimate the width of the $3\ {}^3S_1\ \psi(4.03)$ to $\bar{p}p$:

$$\Gamma(\psi(4.03) \to \bar{p}p) \sim \left(\frac{3.1}{4.0}\right)^7 \Gamma(\psi \to \bar{p}p) \sim 20\ eV \tag{3.5}$$

Then the branching ratio is

$$B(\psi(4.03) \to \bar{p}p) \sim 4 \cdot 10^{-7} \tag{3.6}$$

and the cross section at the peak is

$$\sigma(\bar{p}p \to \psi(4.03)) \sim\ 0.5\ nb \tag{3.7}$$

With $\mathcal{L} = 10^{31}\text{cm.}^{-2}\text{sec.}^{-1}$ this corresponds to 50,000 events for a run of 10^7 sec. I would then guess that this is also the order of magnitude of the total charm cross section above $\bar{D}D$ threshold and of the charmed baryon cross section.

Since bottomonium is a more nearly nonrelativistic system with smaller strong interaction corrections and a wealth of narrow states below $\bar{B}B$ threshold, it would be very rewarding to study it in $\bar{p}p$ annihilation. Energetically this would be possible in collider mode, but if the counting rules are a reliable guide the cross sections are far too small. For $\mathcal{L} = 10^{30}\text{cm.}^{-2}\text{sec.}^{-1}$ and a run of $T \sim 10^7$sec., I find that the corresponding numbers of events are $N(\Upsilon \to e^+e^-) \sim 5$, $N(\eta_b \to \gamma\gamma) \sim 0.1$, and $N(\chi_b(2^{++}) \to \gamma\Upsilon \to \gamma e^+e^-) \sim 0.4$. A luminosity of at least 10^{32} and preferably 10^{33} is needed to make this feasible.

Protonium Atom

Some recently established properties of the $\bar{p}p$ atom, described by Kilian in his review of results from LEAR, may prove very useful – for instance, in meson spectroscopy as discussed in the next subsection. Because of its small size, $r \sim 60$ fm., the protonium atom in a liquid H_2 medium can approach very near to large electric fields that induce rapid nonradiative transitions, by Stark mixing, to s-states which then annihilate by strong interactions (Day–Snow–Sucher effect). The Asterix experiment has verified that at least 90% of stopped $\bar{p}$'s in liquid hydrogen annihilate by this mechanism from L = 0 initial states.

In gaseous hydrogen, Stark mixing is diminished by the lower density and stopped $\bar{p}$'s annihilate from both L = 0 and L = 1 in roughly comparable proportions. However there is a beautiful tag for L = 1 annihilations: 13± 2% of all annihilations in gas are accompanied by an L-series X-ray of $1\frac{1}{2}$ to 3 keV indicating a transition from an outer orbital to the 2p level. About 2% of these 2p states decay radiatively to the ls level, while the remaining 98% annihilate strongly from the 2p state.

There is considerable interest in the physics of the protonium atom. Broadening of the ground state due to annihilation has already been seen. By studying shifts of energy levels and line-widths we are sensitive to unexpected long distance effects, such as strong Van der Waals forces or axion-like objects.[17]

Meson Spectroscopy

Talks were presented on meson spectroscopy by Lipkin, Sharpe, and Isgur. While there are good candidates, there is still no definitive identification of the glueball states whose existence is one of the most striking predictions of QCD. We also expect to find $\bar{q}qg$ meiktons (a.k.a. hermaphrodites or hybrids) and four quark states, $\bar{q}\bar{q}qq$, both with exotic and nonexotic quantum numbers. Relativistic dynamics and confinement would also give rise to $\bar{q}q$ states beyond the nonrelativistic spectrum, e.g., cavity or string excitations. In the nonexotic channels the study of these new objects is tied inextricably to a precise understanding of the ordinary $\bar{q}q$ spectrum: we need to know reliably the states that are $\bar{q}q$ mesons in order to identify those that aren't and the new states may be mixed, by amounts we cannot now hope to predict, with the ordinary ones.

Progress has been slow, chiefly because it has been statistics-limited. Bump hunting is inadequate – there are too many states above 1 GeV to be able to match a bump of unknown spin to a given resonance (I have this concern for instance about the "f" signal

of the Asterix group discussed by Kilian). Partial wave analysis is absolutely essential, requiring very high statistics to overcome backgrounds and ambiguities that increase with increasing mass. The history of the field is that each advance in statistics has allowed us to see more structure (especially in nonleading partial waves) and to carry the region of unambiguous analysis to higher mass.

Figure (3.1) shows how far we have to go. It is my private version of the present state of the ordinary $\bar{q}q$ spectrum, truncated at L = 3. A conservative interpretation of the data suggests that after all these years only 3 (three!) $\bar{q}q$ nonets are unambiguously complete: π, ρ, and A_2. Two years ago I would have included the A_1 nonet, but that is now in doubt given new uncertainty as to whether there is a 1^{++} E(1420). I do not count the 0^{++} nonet as complete because of controversy as to the interpretation of S* and δ (which I personally suspect are $\bar{q}\bar{q}qq$ states). This is a shocking state of affairs and it is directly linked to our present inability to cleanly identify gluonic states.

In addition to the statistical power that can be brought to bear, $\bar{p}p$ annihilation at rest has another advantage related to the properties of the $\bar{p}p$ atom discussed in the preceding subsection. In his talk Jaffe gave a very nice example of how the predominance of the L = 0 state in annihilation at rest in liquid hydrogen can be used to look for new physics in $\bar{p}p \to \eta\pi\pi$. I want to describe another example, in the channels

$$(\bar{p}p)_{L=0,1} \to X + \begin{cases} \pi\pi \\ \pi/\eta/\eta'/K. \end{cases} \tag{3.8}$$

When the system X has mass M_X that places it near the edge of phase space in (3.8), quantum numbers $J^{PC}(X)$ will be favored that allow zero orbital angular momentum in the final state. The favored quantum numbers for $J^{PC}(X)$ are shown in table (3.1)

	$L=0$	$L=1$
$X\pi\pi$	$0^{-+}, 1^{--}$	$1^{+-}, (0,1,2)^{++}$
$X+\pi/\eta/\eta'/K$	$0^{++}, 1^{+-}$	$1^{--}, (0,1,2)^{-+}$

Table 3.1 Favored $J^{PC}(X)$ for $\bar{p}p$ annihilation at rest

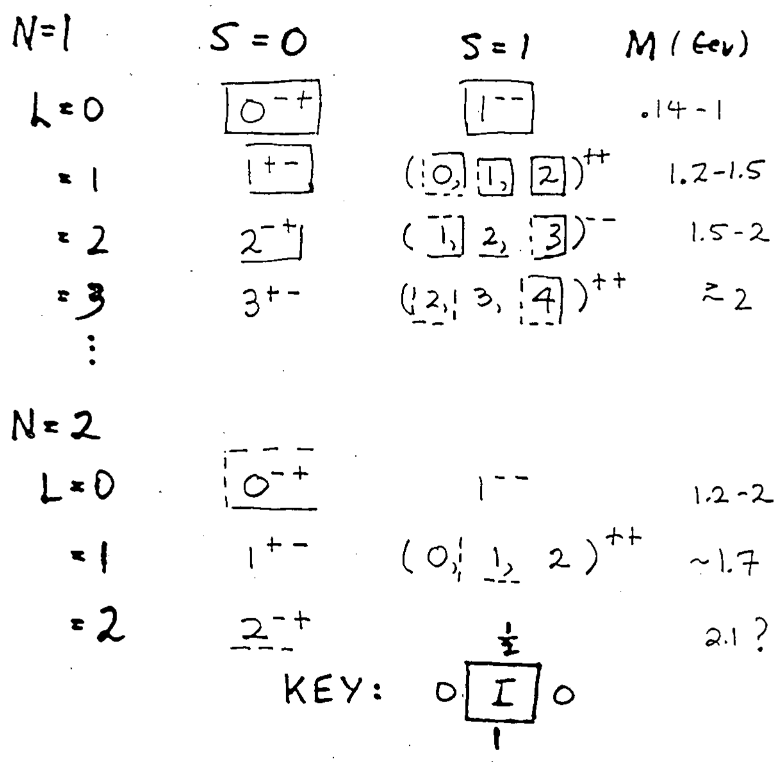

Figure 3.1 A private version of the present status of the $\bar{q}q$ spectrum for $L \leq 3$.

As discussed in the preceding subsection, L = 0 annihilations dominate for stopped $\bar{p}$'s in liquid hydrogen while L = 1 annihilations may be tagged in hydrogen gas using the accompanying L–series X–ray.

I came across this selection rule[18] while puzzling over $\bar{p}p$ annihilation data in liquid hydrogen at rest and in flight ($p_{LAB} \sim 700 MeV/c$). As shown in fig. (3.2) the latter[19] has peaks at both D(1270) and "E" (1420) while the former[20] has only a peak at the "E". This could be understood if the "E" seen in annihilation at rest was not the putative $J^{PC} = 1^{++}$ partner of D it was assumed to be in 1980 but rather a pseudoscalar particle (as indeed claimed originally in ref. 20), to be identified with the particle then discovered in radiative ψ decay. This hypothesis was supported by subsequent spin–parity analysis of the particle in radiative ψ decays, showing it to be a pseudoscalar (and (re)naming it "iota"). Comparing D signals in figure (3.2) suggests that the selection rules of Table (3.1) may be quite effective, since $(\bar{p}p)_{L=0} \to D\pi\pi$ only requires one unit of orbital angular momentum in the final state.

The enhanced channels in Table 3.1 are auspiciously chosen. $J^{PC} = 0^{-+}$ and 0^{++} are prime channels for low-lying glueballs, as discussed by Sharpe. It is a good omen for glueball hunting in $\bar{p}p$ annihilation that the glueball candidate iota is apparently seen there at a sizeable rate ($B \sim 2 \cdot 10^{-3}$) with little background. Thus two of the four favored channels in liquid hydrogen are of great interest. The eight favored channels for $L = 1$ annihilation are also aptly chosen, corresponding precisely to the quantum numbers of the eight lowest-lying meikton nonets computed in the bag model. The $J^{PC} = 1^{-+}$ channel is a $\bar{q}q$ exotic in which ground–state meiktons are expected to occur. The channel $X + \pi/\eta/\eta'$ has the added advantage that we may "scan" different ranges in M_X by choosing the recoil particle π, η, or η'.

What level of statistics is needed? Consider the accomplishments of the ACCMOR experiment[21] at the CERN SPS which accumulated 600,000 $\pi^-\pi^-\pi^+$ events in the channel $\pi^- p \to \pi^-\pi^-\pi^+ p$. Having much more statistics then previous experiments they were able to go to larger momentum transfers, thereby resolving the puzzle over the putative $A_1(1070)$ versus the Deck effect. They found the A_1 at a larger mass, 1230–1280 MeV, a result subsequently confirmed by other experiments. They found evidence for 7/9 (π' and K') of the radially excited pseudoscalar nonet, which is crucial for eventual understanding of the

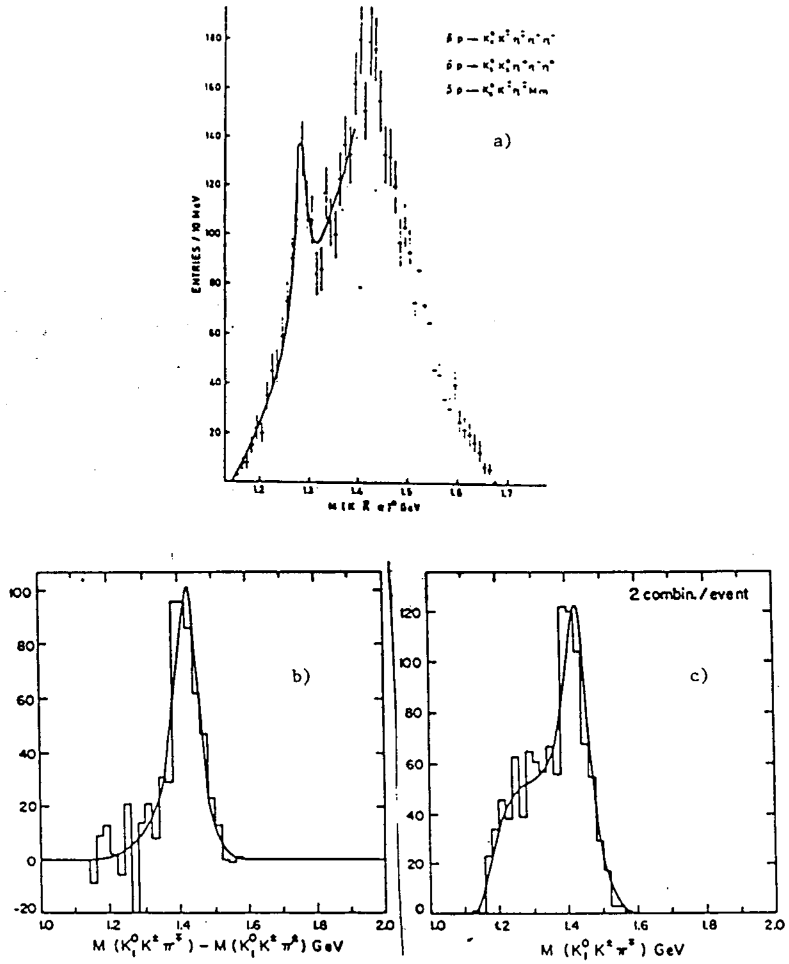

Figure 3.2 $\bar{p}p$ annihilation to $\bar{K}K\pi$ recoiling against $\pi\pi$. Figure (a) taken from ref. (18) with p_{LAB} = 700–760 MeV/c has both "D" and "E" peaks while figures (b) and (c) from ref. (19) with p_{LAB} = 0 show only an "E" peak.

glueball candidate $\iota(1450)$. They found evidence for radially excited p–wave states, A_1' and A_2', both at $\sim$ 1700 MeV. They established the d–wave state, $A_3(1680)$, $I, J^{PC} = 1, 2^{-+}$ and observed a second intriguing enhancement in the same channel at 1850 MeV. If there is indeed a second resonance in the channel at 1850 MeV, it is too light to be the radial excitation of $A_3(1680)$ and must represent new physics, perhaps the $J^{PC} = 2^{-+}$ meikton expected in that mass range. However the ACCMOR analysis was overcome by ambiguities in this mass region, so that the enhancement at 1850 could not be confirmed or clearly interpreted. The moral is that the 600,000 events yielded many important results but were not sufficient to carry the unambiguous analysis beyond $\sim$ 1700 MeV in an interesting nonleading partial wave.

As Lipkin emphasized in his talk, no single experiment can alone identify gluonic states. It would take much firmer theoretical mastery than our present primitive understanding for that to be conceivable. Rather we will have to put together information from many different experiments, relying on a growing knowledge of the $\bar{q}q$ spectrum against which the new states must be recognized.

Consider for example the iota (1450), the most prominent state in radiative ψ decay, a good glueball channel since it proceeds perturbatively by $\psi \to \gamma gg$. Besides its large coupling to gluons, iota has a small coupling to photons, now bounded[22] by $\Gamma(\iota \to \gamma\gamma) < 1.6\ \mathrm{keV}/B(\iota \to \bar{K}K\pi)$. This makes iota an extremely sticky object, the stickiness[13] S_X of a particle X being the ratio of its gg coupling to its $\gamma\gamma$ coupling as measured in $\psi \to \gamma X$ and $X \to \gamma\gamma$:

$$S_X = \frac{\Gamma(\psi \to \gamma X)}{\Gamma(X \to \gamma\gamma)} \cdot \frac{LIPS(X \to \gamma\gamma)}{LIPS(\psi \to \gamma X)} \tag{3.9}$$

where LIPS stands for Lorentz Invariant Phase Space. If we normalize $S_\eta = 1$ then the relative stickiness of ι, η', and η is

$$S_\iota : S_{\eta'} : S_\eta \cong \gtrsim 60 : 4 : 1. \tag{3.10}$$

The lower limit on $S_\iota/S_{\eta'}$ is striking but not definitive evidence in favor of the glueball interpretation of iota. By tuning the flavor content of a radially excited $\bar{q}q$ state we could make the $\gamma\gamma$ width small and the stickiness large. For instance, if iota were the $\bar{s}s$ radially excited pseudoscalar, its $\gamma\gamma$ width would be small. It would then be the ninth pseudoscalar in the π' nonet, consisting in addition of $\pi'(1300)$, $K'(1400)$, and $\zeta(1270)$, the latter being an isoscalar with flavor content $(\bar{u}u + \bar{d}d)/\sqrt{2}$ if iota were $\bar{s}s$. Naive SU(3) would then predict

$$\Gamma(\psi \to \gamma\varsigma) \cong 2\Gamma(\psi \to \gamma\iota) \tag{3.11}$$

in gross disagreement with the data. However under this scenario $\psi \to \gamma\iota$ might be enhanced by the same helicity argument (discussed in section 2 above in connection with the $\xi(2230)$) that has been used to explain why $\iota \to \bar{K}K\pi$ dominates if ι is a glueball[10]: namely, the enhancement of $gg \to \bar{s}s$ in the J = 0 channel.

This picture of iota as an $\bar{s}s$ state is a possibility, though where I believe it flounders is in explaining why radiative ψ decay indicates a stronger gg coupling for ι than for η and η'. It is also not clear that this reasoning can accomodate the observed ratio of $\Gamma(\psi \to \gamma\eta)/\Gamma(\psi \to \gamma\eta')$.

Putting these speculations aside, the real heart of the matter is that we need to understand the π' nonet in order to understand iota. There is now evidence for 8/9 of the π' nonet. The $\pi'(1300)$ is the best established while $K'(1400)$ is still in doubt and $\varsigma(1270)$ has now been seen in two experiments.[23] If we accept these masses, then the degeneracy of π' and ς suggests ideal mixing so that the ninth state, ς', would naively have a mass of $m_{\varsigma'} \cong 2m_{K'} - m_{\varsigma} \cong 1500$ MeV. For now the K' mass is too poorly known to take this estimate very seriously.

First of all we need to know whether there is a <u>tenth</u> pseudoscalar in this mass region in addition to the nine already known. If so, we must next study the properties of these ten states to decide how they fit into a nonet and how the three isoscalars are mixed. High statistics $\bar{p}p$ annihilation experiments have crucial contributions to make to this program, along with high statistics studies in πp and Kp scattering, $\gamma\gamma$ scattering, and radiative ψ decay. Putting together the data from all these sources we will eventually understand iota and other examples of the new physics that is hidden among the $\bar{q}q$ states of the meson spectrum.

IV. Conclusions

I will conclude by summarizing the advantages and disadvantages of such a facility. I see one advantage – lots of first rate physics at bargain basement prices – but I also see three disadvantages. First, the experiments are for the most part very difficult (backgrounds, rates ...), requiring considerable ingenuity and effort. Second, some of the money saved on the low cost of machine facilities would have to be spent on at least one or two powerful general purpose detectors. Third, it may be necessary to erect a fence around the laboratory perimeter to keep Fermilab from being overrun by the enthusiastic communtity of potential users.

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