$\bar{P}P$ - PHYSICS IN THE milli-TeV REGION *

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When the organizers of this workshop asked me to give an overview of the physics opportunities at a new low energy $\bar{p}p$-facility, I was reluctant. As anyone who has followed low energy $\bar{p}p$-physics knows, it has a long and often sad history. Experimenters and theorists alike have spent much of their time following false leads, and significant discoveries have been rare. I have not worked in the field for nearly a decade and was not eager to begin again. I agreed to talk with the understanding that I was inclined to be skeptical of the potential of a new $\bar{p}p$-facility, but would do my homework and report my conclusions nevertheless.

The organizers must have been confident that the physics would speak for itself: for in the end I am convinced that there is exciting physics to be done at a dedicated $\bar{p}p$-facility with high luminosity, a high quality beam and center of mass energy from threshold up to about 4 mTeV. [1mTeV = 1GeV seems a natural Fermilab unit.] The purpose of this talk, then, is to lead the reader through the same arguments which convinced me of the physics potential of this machine. I will only discuss physics issues and ignore knotty questions like whether some or all of this program can be carried out at existing machines. Almost nothing in this talk is my own invention, instead it is more of a "book report" gleaned from many sources and I apologize at the outset if I have neglected to give credit for original work which I learned about from secondary sources.

Anyone trying to evaluate the physics potential at a new facility must make clear what he considers important physics, especially at the present time: theoretical particle physics is in a state of turmoil, its traditional values being swept aside by "string fever", and experimental particle physics is plagued by budgetary constraints which force us to scrutinize new initiatives more closely than ever before. At the same time, the nuclear physics community has become interested in problems traditionally associated with particle physics and is building machines (CEBAF, RHIC) for which QCD and the physics of hadrons are principle objectives. Personally, I believe there are two great problems confronting high energy physics:

- What are the origins of the standard model? What are the origins of weak symmetry breakdown, of quark and lepton masses and mixing angles? Why is CP violated? Why are the gauge groups $SU(3)\times SU(2)\times U(1)$ chosen by nature? Theorists have been trying without success to answer these well-defined questions for more than a decade.

- What are the dynamics of confinement in gauge theories? Hadronic phenomena at milli-TeV energies are rich but surprisingly simple. The spectrum follows from the most naive quark models. An effective Lagrangian obtained by adding confinement and dynamical chiral symmetry breaking by hand to the fundamental QCD Lagrangian (some kind of bag model) does a good qualitative job of describing hadronic phenomena. But how does one go beyond naive models? Where, for example, are the extra (gluonic or relativistic) degrees of freedom expected in QCD? How is the relativistic bound state to be described?

Experimental input is desperately needed to make progress on either of these questions. Perhaps superstrings and supercomputers will provide the answers to these questions, but I doubt it. Instead, I expect Nature has surprises in store for us which will only be reveallled by experiment.

There seem to me to be three broad ways in which a first rate $\bar{p}p$-facility can shed light on these issues. Let me list them—they form an outline for the rest of my talk—

- Tests of discrete symmetries: CP, CPT, T, $\Delta S=\Delta Q$. These (CP and T in particular) probe the standard model where we least understand it.
- Heavy quark QCD: It should be possible to discover at least three previously unknown narrow states of charmonium, to measure precisely the widths of all narrow $c\bar{c}$-states and to unravel the helicity structure of the $\bar{p}p\rightarrow$charmonium vertex for all narrow charmonium states, providing a great deal of new data on QCD where we are well prepared to make use of it.
- Voodoo QCD[1]: By means of precise, high statistics measurements of exclusive final states observed in $\bar{p}p$-annihilation at rest and in flight it may be possible to
  - observe CP-exotic mesons
  - significantly clarify the glueball spectrum
  - sort out meson spectroscopy in the 1-2 mTeV region
  - produce and study the (broad, overlapping) resonances expected in the $\bar{N}N$-channel.

Many of the traditional issues in $\bar{p}p$-physics are missing from this short list. Some are interesting in themselves but have no direct bearing on the two problems I mentioned at the outset, other seem to me to be raised in unreliable physical models or concerned with phenomena which don't appear to exist in Nature. Among these are: the search for narrow baryon-antibaryon bound states or resonances above threshold ("baryonium"); the study of "annihilation mechanisms", eg. $^3P_0$, quark rearrangement, etc.; the attempt to obtain short and intermediate range $N\bar{N}$-interactions from NN-interaction models; the attempt to create and study a quark-gluon plasma by annihilating $\bar{p}$'s within a nucleus. Most of these topics are discussed elsewhere in these proceedings. I've omitted $\bar{p}$-atoms and the study of trapped and bottled antiprotons because I am unfamiliar with them and am unable to judge their physics potential.

I. Tests of Discrete Symmetries

New and/or more precise tests of CP-, CPT-, and T-invariance and of the $\Delta S=\Delta Q$ rule will be possible at a dedicated low energy $\bar{p}p$-facility. Violation of CP-invariance in the neutral kaon system has been known since 1964.[2] At present all CP-violation in the neutral kaon system is consistant with a single, "superweak" mixing parameter ε.[3] Present data on $K_L \rightarrow 2\pi$ are consistant with CPT-invariance within two standard deviations.[4] This is by far the most sensitive test of CPT invariance and the existance of a discrepancy is somewhat disturbing. Regardless of whether or not CPT is a good symmetry, the observed violation of CP-invariance in $K_L \rightarrow 2\pi$, together with unitarity, requires T-invariance violation in the neutral kaon system.[5] There is no known evidence for failure of the $\Delta S=\Delta Q$ rule.

Most of the proposed tests of discrete symmetries in $\bar{p}p$-interactions merely use $\bar{p}p$-annihilation as a particularly clean source of neutral kaons. I will limit myself to these. The very interesting possibility that CP-violation could be observed in processes like $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ or $\bar{p}p \rightarrow \bar{\Xi}\Xi$ has been raised by Donoghue at this workshop.[6] The basic idea for precise studies of the neutral kaon system in $\bar{p}p$-annihilation is due to Gabathuler and Pavlopoulos.[7] They propose to look at $\bar{p}p \rightarrow K^+\pi^-\bar{K}^0$ and $\bar{p}p \rightarrow K^-\pi^+K^0$ at rest. Each accounts for about 0.2% of $\bar{p}p$-annihilations at rest. The trick is to trigger on $K^\pm\pi^\mp$ and thereby reconstruct the production vertex, four momentum and <u>strangeness</u> of the produced neutral kaon. Subsequent observation of 2π, 3π , $\pi^+\ell^-\nu$ or $\pi^-\ell^+\bar{\nu}$ decays as functions of proper time along the neutral kaon trajectory tests discrete symmetries. The advantages of this approach over traditional regeneration experiments are that the neutral kaon strangeness is known at production and the systematics are totally different: there is no neutron background and the experiment is performed in the $\bar{p}p$-center of mass with 4π geometry. Specific tests which have been proposed are:

Measurement of CP-violation parameters and a test of CPT-invariance in $K_L \to 2\pi$[3]

This is a well known and exhaustively studied system. All CP- or CPT-violating effects are determined by the famous parameters ε and ε'. In the limit of CPT-invariance ε measures CP-violation in the $K^0/\bar{K}^0$ mass matrix and ε' measures CP-violation in the $K_2(CP=-1) \to \pi\pi(CP=+1)$ amplitude. Whether or not CPT is violated, ε and ε' are related to the measured parameters η_{+-} and η_{00} by

$$\eta_{+-} = \frac{K_L \to \pi^+\pi^-}{K_S \to \pi^+\pi^-} = \varepsilon + \varepsilon'$$

$$\eta_{00} = \frac{K_L \to \pi^0\pi^0}{K_S \to \pi^0\pi^0} = \varepsilon - 2\varepsilon'$$

At the moment only ε is known to be non-zero—$|\varepsilon| \simeq 2.3 \times 10^{-3}$. The best values for η_{00} and η_{+-} are[8]

$$|\eta_{+-}| = 2.274 \pm 0.022 \times 10^{-3} \qquad \phi_{+-} = 44.6^\circ \pm 1.2^\circ$$

$$|\eta_{00}| = 2.33 \pm 0.08 \times 10^{-3} \qquad \phi_{00} = 54^\circ \pm 5^\circ$$

If CPT invariance is assumed, then the phases of both ε and ε' are determined:[3,4]

$$\arg\varepsilon = \tan^{-1}\frac{2(m_L - m_S)}{\Gamma_S - \Gamma_L} = 43.74^\circ \pm 0.14$$

$$\arg\varepsilon' = \delta_2 - \delta_0 + \pi/2 = 44.7^\circ \pm 4.6^\circ$$

(δ_0 and δ_2 are the s-wave $\pi\pi$ phase shifts at $\sqrt{s} = m_K$ for $I = 0$ and 2 respectively.) Since $|\varepsilon'/\varepsilon|$ is known to be very small, one expects $\phi_{00} - \phi_{+-}$ to be very small. Instead, the most accurate value.[9] $\phi_{00} - \phi_{+-} = 12.6^\circ \pm 6.2^\circ$, and the world average,[8] $\phi_{00} - \phi_{+-} = 9.8^\circ \pm 5.4^\circ$, are roughly two standard deviations from zero. A more precise measurement of ϕ_{00} is necessary to put to rest this apparent violation of CPT invariance.

If CPT is assumed, then the phases of ε and ε' are practically equal and

$$|\varepsilon/\varepsilon'| \cong \frac{1}{6}\left(1 - \frac{|\eta_{00}|^2}{|\eta_{+-}|^2}\right)$$

Two recent experiments have placed rather stringent limits on $|\varepsilon'/\varepsilon|$ (assuming CPT):

$$|\varepsilon'/\varepsilon| = 1.7 \pm 7.2 \pm 4.3 \times 10^{-3}$$ [10]

$$|\varepsilon'/\varepsilon| = -4.6 \pm 5.3 \pm 2.4 \times 10^{-3}$$ [11]

These limits are close to the lower bounds on $|\varepsilon'/\varepsilon|$ in the standard model.[2]

By measuring the rates for $K^0/\bar{K}^0 \to \pi^+\pi^-$ and $K^0/\bar{K}^0 \to \pi^0\pi^0$ as functions of proper time along the path of the neutral kaon, one measures η_{+-} and η_{00}. In their LEAR proposal,[12] Adiels et al. estimate an overall improvement in the measurements of both $|\varepsilon'/\varepsilon|$ and $|\phi_{+-} - \phi_{00}|$ of a factor of ≈ 2.5 [See Table I] with a sample of 10^{13} $\bar{p}$-annihilations at rest. By the time this experiment is completed, comparable sensitivity will have been achieved with traditional methods, nevertheless, it is encouraging that the first look at CP and CPT-violation in $K \to 2\pi$ at a $\bar{p}p$-facility expects to surpass the limits now achievable with traditional means.

Direct Tests of CPT [13,14]

The equality of the K^+ and K^- lifetimes

$$\frac{|\tau^+ - \tau^-|}{|\tau^+ + \tau^-|} < 1.5 \times 10^{-3} \quad \text{(present limit)}$$

tests CPT. Measurements on $K_L \to 2\pi$ and theoretical arguments using unitarity (Bell-Steinberger relation[15]) allow one to bound the $K^0/\bar{K}^0$ mass difference:[13]

$$\frac{|M - \bar{M}|}{|M_L - M_S|} < 2.6 \times 10^{-2} \qquad \text{(present limit)}$$

at the level of two standard deviations. Proposals to LEAR would improve both these limits by ~1 order of magnitude [see Table I].

Direct observation of T-invariance violation [13,14,16]

If CPT is unbroken then the observed CP-violation in the neutral kaon system implies violation of time reversal invariance. Even if CPT is violated, the observed CP-violation in $K_L \to 2\pi$, combined with unitarity, requires T-invariance violation in the kaon system. A very pretty way to observe T-violation directly was pointed out by Kabir[16] and proposed at LEAR by Tanner and collaborators.[13,14] The idea is to compare the rate for $K^0 \to \bar{K}^0$ with $\bar{K}^0 \to K^0$ by comparing the reaction chains:

$$\bar{p}p \to K^- \pi^+ K^0 \qquad \text{[A]}$$
$$\quad \llcorner \bar{K}^0$$
$$\qquad \llcorner \pi^+ e^- \bar{\nu}_e$$

$$\bar{p}p \to K^+ \pi^- \bar{K}^0 \qquad \text{[B]}$$
$$\quad \llcorner K^0$$
$$\qquad \llcorner \pi^- e^+ \nu_e$$

The argument relies on (and tests) the $\Delta S = \Delta Q$ rule which forbids $K^0 \to \pi^+ e^- \bar{\nu}_e$ and $\bar{K}^0 \to \pi^- e^+ \nu_e$. Thus the observation of sequence [A] ensures that a produced K^0 has oscillated to $\bar{K}^0$, while [B] ensures that a produced $\bar{K}^0$ has oscillated to K^0. Different rates for [A] and [B] is a direct measure of T-violation. If CPT and $\Delta S = \Delta Q$ are valid, then the known CP-violation in the neutral kaon system predicts the rates for [A] and [B] to differ at a level of 6.5×10^{-3} independent of proper time. CPT-violation in the $K^0/\bar{K}^0$ mass matrix would lead to deviations from this value. A violation of $\Delta S = \Delta Q$ would result in a difference in rates varying in a characteristic way with proper time. The expected signal is shown in Fig. 1.[14]

Strictly speaking this experiment should be regarded as a test of CPT and the $\Delta S = \Delta Q$ rule. Even if these are not violated, however, it would provide a very elegant direct confirmation of the T-violation in the neutral kaon system.

Table I

Proposed tests of discrete symmetries

Parameter	Violates	Present value	Proposed limit	Ref.
$\lvert\tau_+ - \tau_-\rvert/\lvert\tau_+ + \tau_-\rvert$	CPT	$<1.5\times10^{-3}$	$<1.5\times10^{-4}$	14
$\lvert M-\bar{M}\rvert/\lvert M_L - M_S\rvert$	CPT	$<2.6\times10^{-2}$	$<2.6\times10^{-3}$	14
$\phi_{00}-\phi_{+-}$	CPT*	$12.6^\circ\pm6.2^\circ$ [9]	2°	12
$\lvert\varepsilon'/\varepsilon\rvert$	CP	$1.7\pm7.2\pm4.3\times10^{-3}$ [10]	2×10^{-3}	12
		$-4.6\pm5.4\pm2.4\times10^{-3}$ [11]		
$\lvert\eta_{+-0}\rvert^2$	CP	$<1.2\times10^{-1}$ [8]	6×10^{-4}**	12
$\lvert\eta_{000}\rvert^2$	CP	$<10^{-1}$ [8]	8×10^{-4}**	12
Re x	$\Delta S=\Delta Q$	$<2\times10^{-2}$	6×10^{-4}	12
Im x	$\Delta S=\Delta Q$	$<2.6\times10^{-2}$	7×10^{-4}	12
K^+e^+/K^-e^-	T,CPT or $\Delta S=\Delta Q$*	—	10^{-3}	14

*see text
**It is unclear from Ref. 12 whether this limit applies to $\lvert\eta\rvert$ or $\lvert\eta\rvert^2$.

Measurement of CP violation in $K_S\to3\pi$ [2]

By measuring the rate for $K^0/\bar{K}^0\to\pi^+\pi^-\pi^0$ and $3\pi^0$ as functions of proper time along the path of the neutral kaon it will be possible to obtain accurate measurements of the CP-violation parameters in $K_S\to3\pi$. The sensitivity anticipated by Adiels et al.[12] is summarized in Table I. The improvements appear significant, but to understand the importance of these measurements we will have to review the way CP-violation manifests itself in $K_S\to3\pi$.[17] We label the pions π_0, π_1, and π_2, where π_1 and π_2 are charged in the $\pi^+\pi^-\pi^0$ mode. The decay amplitudes for the CP-eigenstates K_1(CP=+1) and K_2(CP=−1) can be decomposed according to the isospin of the 3π-system:

$$M(K_\alpha \to \pi_1\pi_2\pi_0) = C[iA^0_\alpha(E_1-E_2)(E_2-E_0)(E_0-E_1)/M^3 + A^1_\alpha e^{i\delta_1} + B^1_\alpha e^{i\delta_1'}(E_0-Q/3)/M + iA^2_\alpha e^{i\delta_2}(E_1-E_2)/M + A^3_\alpha e^{i\delta_3}]$$

where $\alpha=1$ or 2 for K_1 or K_2, $Q=E_0+E_1+E_2$ and the superscripts on the amplitudes A^I and B^I denote the isospin of the three pion system. With the exception of the $I = 1$ amplitude, only the first term in an expansion in the pion energies has been kept. The P, C and CP properties of the amplitudes A^I and B^I and facts relating to their role in $K\to 3\pi$ are summarized in Table II. For comparison, the properties of the analogous amplitudes in $K\to 2\pi$ are summarized in Table III.

Table II

Properties of $K\to 3\pi$ Amplitudes

	3π quantum numbers			$K_1\to 3\pi$ conserves			$K_2\to 3\pi$ conserves				
Amplitude	P	C	CP	P	C	CP	P	C	CP	$\pi^0\pi^0\pi^0$	ΔI
A^0	−	−	+	✓	✓	✓	✓	×	×	NO	1/2
A^1	−	+	−	✓	×	×	✓	✓	✓	YES	1/2, 3/2
B^1	−	+	−	✓	×	×	✓	✓	✓	YES	1/2, 3/2
A^2	−	−	+	✓	✓	✓	✓	×	×	NO	3/2, 5/2
A^3	−	+	−	✓	×	×	✓	✓	×	YES	5/2, 7//2

Table III

Properties of $K\to 2\pi$ Amplitudes

	2π quantum numbers			$K_1\to 2\pi$ conserves			$K_2\to 2\pi$ conserves				
Amplitude	P	C	CP	P	C	CP	P	C	CP	$\pi^0\pi^0$	ΔI
A_0	+	+	+	×	×	✓	×	✓	×	YES	1/2
A_2	+	+	+	×	×	✓	×	✓	×	YES	3/2 5/2

The parameters measured in $K \to 3\pi$ are defined in analogy to those measured in $K \to 2\pi$:

$$\eta_{000} = \frac{K_S \to 3\pi^0}{K_L \to 3\pi^0} \qquad \eta_{+-0} = \frac{K_S \to \pi^+\pi^-\pi^0}{K_L \to \pi^+\pi^-\pi^0}$$

From Table II it is clear that the decay $K_1 \to 3\pi^0$ violates CP. In contrast, the decay $K_1 \to \pi^+\pi^-\pi^0$ conserves CP in $I = 0$ and $I = 2$. The CP-violating $K_1 \to \pi^+\pi^-\pi^0$ ($I = 1$ and $I = 3$) amplitudes can be isolated by symmetrizing in $E_{\pi+} \leftrightarrow E_{\pi-}$. If we assume that there are no $\Delta I \geq 5/2$ terms in the weak Hamiltonian then the $I = 3$ final state can be ignored, leaving all CP-violation in $3\pi^0$ and $\pi^+\pi^-\pi^0$ the $I = 1$ amplitude. Since three pions can couple to $I = 1$ in several different ways, η_{000} and η_{+-0} are independent. η_{000} is a symmetric function of the pion energies so

$$\eta_{000} \sim \eta^0_{000} + O(E^2)$$

The CP-violating part of η_{+-0} is symmetric in $E_{\pi+} \leftrightarrow E_{\pi-}$ so

$$\eta_{+-0} \sim \eta^0_{+-0} + \eta'_{+-0}(E_0 - Q/3) + O(E^2)$$

So three constants extracted from the Dalitz plot contain all the information on CP-violation in the $K_S \to 3\pi$ decay (to $O(E^2)$ and ignoring $\Delta I \geq 5/2$). The physical K_S is a linear superposition of K_1 and K_2: $K_S \sim K_1 + \epsilon K_2$, so CP-violation in η_{000} and η_{+-0} can arise either from the small admixture of K_2 in K_S or from direct CP-violation in the K_1 decay amplitude.

<u>Theoretical Expectations</u> [2]

What do theorists expect to learn from these experiments? and given the expectations of Table I how important is it that the experiments be done?

*** <u>$K \to 2\pi$</u>: Even marginal improvements in the current limits on $|\epsilon'/\epsilon|$ are interesting, so is the hope of clearing up the confusion over $\phi_{00} - \phi_{+-}$. The fact that a first generation $K \to 2\pi$ experiment is competitive with the best using standard methods is quite encouraging.

** CPT: It is difficult to construct a reasonable framework for relativistic quantum mechanics in which CPT is not automatic. It follows from Lorentz invariance in any local field theory. If it were violated, it would be extraordinarily important.

** T: CP-violation requires T-violation at a predicted level. It would be nice to verify it explicitly. The experiment is a classic, but it is not "new".

** CP-violation in $K \to 3\pi$: Major improvements in the limits on η_{000} and η_{+-0} are possible. However, it is likely that little will be learned from these greatly improved measurements. To see why, we must consider the predictions for η_{000} and η_{+-0} in various models:

- Superweak: If the only CP-violation is in the kaon mass matrix $\eta_{000} = \eta_{+-0} = \varepsilon$.
- Standard model (a la Kobayashi-Maskawa): There is only one CP-violating phase in the fermion mass matrix. It can be taken as the relative phase of the {8} and {27} pieces of H_W. PCAC together with an analysis of final state interactions gives the CP-violating amplitudes in $K_S \to 3\pi$ in terms of ε',[18] so

$$\eta_{000} = \varepsilon + O(\varepsilon')$$

$$\eta_{+-0} = \varepsilon + O(\varepsilon'),$$

  and the deviation from the superweak result will be too small to detect with the anticipated sensitivity. The same remarks apply to models with Higgs generated CP-violation.[2]
- New physics: It is clear from Table III that CP-violation in $K_L \to 2\pi$ comes entirely from P-odd operators. In $K_S \to 3\pi$ it comes from P-even, C-odd operators. Thus, models with new, C- and CP-volating, but P-conserving interactions can be constrained (or discovered) by bounding (or detecting) deviations from the superweak predictions for η_{000} and η_{+-0}.[2]

* $\Delta S = \Delta Q$: Violation of this rule is not expected above the level of 10^{-14} in the standard model. I know of no interesting models with $\Delta S = \Delta Q$ at the level of sensitivity of these experiments.

The best summary of the tests of discrete symmetries available at a new $\bar{p}p$-facility is probably the projected limits given in Table I taken from the latest LEAR proposals.

II. A New Era in Charmonium Spectroscopy

To discuss the potential of a dedicated $\bar{p}p$-facility for charmonium physics it is convenient to assume some definite machine parameters. In the following I have chosen

$$L = 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$$

$$E_{CM} > 4\,\mathrm{mTeV}$$

$$\Delta p/p \text{ as small as } \approx 2\times10^{-5} \text{ or as large as } 10^{-3}.$$

With these parameters a very rich program in charmonium physics will be accessible.[19-23] The hope for bottomonium physics is much more remote. If the achievable machine parameters are different, then of course, the physics potential must be scaled up or down accordingly. With this machine it would be possible to:

- Discover three previously unknown narrow states: $^1P_1\,(J^{PC} = 1^{+-})$, $^3D_2\,(J^{PC} = 2^{--})$, $^1D_2\,(J^{PC} = 2^{-+})$ and confirm the weak η_c'.
- Accurately measure total widths for all narrow $c\bar{c}$-states: Except for the $^3S_1$-states, these are not well known at present. The widths can perhaps be measured as well as ~70 KeV.
- Measure helicity amplitudes in $\bar{p}p$-production : There are several helicity amplitudes for creating each charmonium state (except J=0). These can be separated by studying decay angular distributions. The amplitudes may contain information about chiral symmetry violation in QCD.
- Unravel multipoles: Radiative decays of $c\bar{c}$-states often allow competing multipoles. For example $2^{-+}\rightarrow 1^{--}$ via M1, E2 or M3 (etc.) Once again, decay angular distributions allow these to be separated.

The physics motivation to perform these measurements is quite compelling. The masses of the $^1P_1$, $^3D_2$ and $^1D_2$ states are sensitive to spin, spin-orbit, tensor and relativistic terms in the charmonium potential. There is still considerable uncertainty about the nature of these terms.

The total widths of narrow charmonium states are dominated by $c\bar{c}$-annihilation into two or three gluons. They are "predicted" in QCD in terms of the running coupling $\alpha_c(M^2)$ and the wavefunction at the origin (or its derivatives). The $\bar{p}p$-couplings to specific charmonium states probe QCD at a mass scale ~3-4 mTeV, where most measures of chiral symmetry breaking in QCD, with the exception of the proton mass, are small:

$$\langle \bar{u}u \rangle^{1/3} << M_{J/\psi}$$

$$m_{u,d} << M_{J/\psi}$$

It is tempting to ignore the proton mass and argue that chiral symmetry is effectively restored at these energies, so that only chirally invariant couplings between $\bar{p}p$ and charmonium states should be allowed.[24] Thus, for example, the η_c should decouple from $\bar{p}p$ (just as the Higgs decouples from massless fermions), and the J/ψ coupling should be pure Dirac, ie. $\bar{p}\gamma^{\mu}p\psi_{\mu}$, with no $\bar{p}\sigma^{\mu\nu}q_{\nu}p\psi_{\mu}$ term.[24] In fact these predictions do not seem to work very well. For example, the coupling of the η_c to $\bar{p}p$ is comparable to the J/ψ to $\bar{p}p$. It would be very interesting to find a way to estimate the relative magnitude of chiral symmetry violating and preserving terms.

The possibility of doing significant charmonium physics at a $\bar{p}p$-facility relies on the excellent momentum resolution of cooled $\bar{p}$-beams, which can be used to enhance the signal compared to background on resonance. This makes it possible to measure charmonium widths directly by scanning over the beam energy. Of course, it also relies on the fact that narrow charmonium states can be produced with appreciable cross sections (~μbarns) <u>without restriction</u> to $J^{PC}=1^{--}$. Most important, the significant branching ratio of narrow charmonium states to $J/\psi+X$ provides an excellent signature (via $J/\psi \to e^+e^-$) which can be used to distinguish charmonium production from the huge background of ordinary hadronic processes at a high luminosity $\bar{p}p$-facility. Specific examples of the reaction chains leading to clear signatures are given in Table IV.

This sounds like an ambitious program. How can we be sure that it will work? Fortunately, precisely this technique was used in the last experiment performed at the ISR—ISR R704[25]—to produce the J/ψ, η_c, χ_1 and χ_2 states. There is even some evidence that the $^1P_1$ was also seen in R704. The χ_1 and χ_2 excitation curves measured in ISR R704 are shown in Fig. 2 along with the sort of data the authors of Ref [25] hope to obtain in from a dedicated $\bar{p}p$-facility.

Table IV

Signatures for Some Charmonium States

$$\bar{p}p \rightarrow {}^3P_2 \rightarrow J/\psi + \gamma_{E1} \rightarrow [e^+e^-] + \gamma_{E1}$$

$$\bar{p}p \rightarrow {}^1P_1 \rightarrow J/\psi + \pi^0 \rightarrow [e^+e^-] + \pi^0$$

$$\bar{p}p \rightarrow {}^3D_2 \rightarrow \chi + \gamma_{E1} \rightarrow J/\psi + \gamma_{E1} + \gamma_{E1} \rightarrow [e^+e^-] + \gamma_{E1} + \gamma_{E1}$$

$$\bar{p}p \rightarrow {}^1D_2 \rightarrow J/\psi + \rho^0 \rightarrow [e^+e^-] + \rho^0$$

It is worth pursuing this further in order to see if the machine assumed at the outset actually has the sensitivity to discover new states and measure their properties in detail. Let me consider three scenarios:

- Search: Look for a state of width ~1 MeV by taking 100 steps over an interval of 100 MeV in a month. To obtain 10 events in the chain:

  $$\bar{p}p \rightarrow X_J \rightarrow Y$$

  where Y is observed (with a theorist's efficiency of 100%), we require:

  $$(2J+1) \cdot BR[X_J \rightarrow \bar{p}p] \cdot BR[X_J \rightarrow Y] > 7.3\times10^{-9}$$

  if the luminosity is 10^{32}.

- Non-specific search: If a particle (X_J) decays to the J/ψ, it is not necessary to know the specific decay mode[19,25]. Instead one can trigger on the inclusive production of e^+e^- pairs at the J/ψ in

  $$\bar{p}p \rightarrow X_J \rightarrow J/\psi + \ldots \rightarrow [e^+e^-] + \ldots$$

A new state appears as a peak in the J/ψ inclusive production as a function of the $\bar{p}p$ center of mass energy. With the same search strategy as the first scenario we require:

$$(2J+1)\cdot BR[X_J \rightarrow \bar{p}p]\cdot BR[X_J \rightarrow J/\psi + \ldots] > 10^{-7}$$

- Bang-up job: Once a state is discovered, measure its width, study decay angular correlations, etc. Assuming this requires ~10^5 events per month in the decay chain:

  $$\bar{p}p \rightarrow X_J \rightarrow Y,$$

  we require:

  $$(2J+1)\cdot BR[X_J \rightarrow \bar{p}p]\cdot BR[X_J \rightarrow Y] > 7.3\times10^{-7}$$

To get a feeling for the potential of this physics let me summarize how the known particles fare. The data--as best I can determine--are summarized in Table V.

Table V

Production of Known Charmonium States in $\bar{p}p$

Particle	Y	$(2J+1)\cdot BR[X_J \rightarrow \bar{p}p]\cdot BR[X_J \rightarrow Y]$
J/ψ	e^+e^-	$3\cdot[2.2\times10^{-3}]\cdot[7.4\times10^{-2}] = 4.9\times10^{-4}$
η_c	$\gamma\gamma$	$4.3\pm3.6\times10^{-7}$ [26]
χ_2	$J/\psi+\gamma \rightarrow [e^+e^-]+\gamma$	$5\cdot[4-10\times10^{-5}]$[19,27] $\cdot[1.2\times10^{-2}] = 2.4-6\times10^{-6}$
χ_1	$J/\psi+\gamma \rightarrow [e^+e^-]+\gamma$	$3\cdot[5\times10^{-5}]$[19] $\cdot[1.7\times10^{-2}] = 3.1\times10^{-6}$

From Table V it is clear that all these particles could be discovered at the envisioned machine and all except perhaps the η_c could be studied in depth.

The branching ratio to $\bar{p}p$ exceeds ~5×10^{-5} for all known $c\bar{c}$-states. If we assume the same is true for the as yet unknown states--$^1P_1$, $^3D_2$, and $^1D_2$--then the non-specific search for these states will succeed if

$$(2J+1)\cdot BR[X_J \rightarrow J/\psi + \ldots] > 2\times10^{-3}.$$

With this criterion in mind let me review the three new, narrow states which might be created at a dedicated $\bar{p}p$-facility and, in particular, their decays to J/ψ:

- $^1P_1(J^{PC}=1^{+-})$—this is the first orbital excitation of the η_c, the charmonium analog of the B-meson. This state is not made in ψ' radiative decays because of its (negative) charge parity. For the same reason, it does not decay to $J/\psi+\gamma$. In principle it can decay to $J/\psi+\pi\pi$, but the Q-value for this decay is probably small and the two pions must be in p-wave relative to the J/ψ. Perhaps the dominant decay leading to a J/ψ is the isospin violating decay, $^1P_1 \rightarrow J/\psi+\pi^0$, which is s-wave and has plenty of phase space. In this context it is well to remember that the (similar) isospin violating decay $\omega \rightarrow \eta\pi^0$ has an 8.7% branching ratio. As far as I know, this decay of the $^1P_1$ has never been estimated.
- $^1D_2(J^{PC}=2^{-+})$—this is the second orbital excitation of the η_c. Although models predict it to lie above 2M(D), this decay is forbidden (by parity). Instead its lowest open charm decay threshold is $D\bar{D}^*$, and its mass is below $M(D)+M(D^*)$ in most models. Thus it is expected to be narrow. It can decay to $J/\psi+\gamma_{M1}$, but the decay requires $\Delta L=2$ and is therefore probably suppressed. Once again, the dominant decay to the J/ψ is probably isospin symmetry violating, $^1D_2 \rightarrow J/\psi+\rho^0$, which is s-wave and has considerable phase space: $M(D)+M(D^*)-M(J/\psi) \cong 775$ MeV.
- $^3D_2(J^{PC}=2^{--})$—this may be narrow for the same reason as the $^1D_2$. Because it is a spin triplet, its radiative cascades to the J/ψ are likely to be important. It can decay to a χ-state by an allowed electric dipole transition, so the $^3D_2 \rightarrow J/\psi+\gamma_{E1}+\gamma_{E1}$ branch is likely to be large. The $^3D_2$ can also decay directly to $J/\psi+\pi^0$ violating isospin symmetry.

In all three cases it seems that the prospects are good for finding a large enough inclusive decay rate to the J/ψ to enable the state to be discovered in this manner. After they are found, experience indicates it is only a matter of time and technique before they are produced in large numbers and studied in depth.

III. Exploring Voodoo QCD

Over the years considerable "collective wisdom" has evolved about confinement dynamics in QCD. There are few reliable quantitative calculations from first principles, but a great deal of qualitative understanding nevertheless. The foundation of this picture is a mix of ideas drawn from sources such as SU(6), quark models, vector dominance, chiral dynamics, QCD sum rules, bag models, parton models, duality, the OZI rule and so forth. So long as they are not taken too quantitatively, these notions provide a very important and predictive guide through the rich phenomena of the strong interactions at low energies. For lack of a better term, I will refer to these ideas collectively as "Voodoo QCD"[1], a name which reflects the mystery and power of the collective wisdom but underestimates its intellectual credentials. To quote Bjorken–originally in reference to the bag model–the subject has "gone from a model to a language without having passed through the intermediate stage of being a theory".[28]

There is much to learn about Voodoo QCD at a dedicated $\bar{p}p$-facility. Most of the interest lies in the meson spectrum in the region below $N\bar{N}$-threshold [1-2 mTeV] and in the $N\bar{N}$-continuum not far above threshold. The meson spectrum below 2 mTeV has proved very complex. It was initially explored in the heyday of stationary target physics. The prominant resonances were identified relatively easily, but the less easily accessed channels remained unexplored. The advent of e^+e^--colliders and especially the study of J/ψ-radiative decays has provided an entirely different perspective on the problem. Eventually the process $\gamma\gamma \rightarrow$ mesons at e^+e^- colliders may contribute with the same impact. It is likely that an equally different and rich view of the meson spectrum from 1 to 2 mTeV will be provided by a $\bar{p}p$-facility. The history of the study of the $\bar{N}N$-continuum is a sorry one. Those of us old enough to remember the bad old days of "baryonium" in the 1970's will not easily be persuaded that there is much to learn from the study of $\bar{N}N$-scattering in the 2-3 mTeV region. Nevertheless, I believe there is a possible program in that region also at a dedicated $\bar{p}p$-facility.

The interest in the meson spectrum between 1 and 2 mTeV centers on the search for glueballs and other exotica predicted by Voodoo QCD but so far not definitively observed.

- <u>glueballs</u> : There are many estimates of the glueball spectrum in QCD. Most, indeed all that respect such principles as Lorentz and guage invariance, share a common set of predictions. [29] The lightest glueballs are expected to be a scalar $[0^{++}]$, a tensor $[2^{++}]$, a pseudoscalar [0^{-+}] and a pseudotensor [2^{-+}]. Mass estimates frequently place most or all of these states below 2 mTeV. A 1^{-+}-glueball, which features prominantly in some models, is probably not among the lightest. Estimates of widths and branching ratios are unreliable. The masses and widths of the 0^{++} and 0^{-+} glueballs are especially uncertain because of their connection with anomalies in the energy momentum tensor and the U(1) axial current in QCD. At present there are several intriguing glueball candidates. The $\iota(1440)$ seen in radiative J/ψ decays–which may yet be the same as the E(1420) seen in hadronic production–is a candidate for the pseudoscalar. The $\theta(1640)$ is a candidate for the tensor. The G(1590) seen in decays into $\eta\eta$ and $\eta\eta'$ at Serpukhov [30] and the $\phi\phi$-resonances seen at Brookhaven[31] are additional glueball candidates.

- <u>CP exotics</u>: A non-relativistic quark-antiquark system with spin S and orbital angular momentum L has parity $P = (-1)^{L+1}$ and charge parity $C = (-1)^{L+S}$. Thus it is forbidden to have the quantum numbers 0^{--} or 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, ... There is no reason for these selection rules to hold in a relativistic theory: They require instantaneous interactions and a kinetic energy which can be separated into a relative and center-of-mass contribution. The selection rules are violated if the mesons contain additional degrees of freedom, eg. $q\bar{q}g$, or by relativistic effects. It is difficult to distinguish the two in a guage invariant way. Mesons made of quarks, antiquarks and (valence) glue have attracted much interest in recent years. They are known variously as meiktons, hybrids and hermaphrodites–little else is known about them,[32] although estimates of their masses lie in the 1-2 mTeV region. One clear signature of such states would be CP-exotics with non-trivial flavor quantum numbers.
- <u>multiquark states</u>: There is a rich spectrum of $q^2\bar{q}^2$-"states" above 1 mTeV strongly coupled to the meson-meson continuum. Rosner (and others)[33] pointed out many years ago that $q^2\bar{q}^2$-"states" above the $\bar{N}N$-threshold should be manifest as prominant, but relatively <u>broad</u> and overlapping resonances in $\bar{N}N$-scattering. This straightforward consequence of duality got lost in all the hysteria about possible <u>narrow</u> multiquark resonances ("baryonium"). The $q^2\bar{q}^2$-"states" below $\bar{N}N$-threshold are in general likely to be broader still, since it is hard to envision any barrier at all preventing them from

falling apart into ordinary mesons. If, however, they couple dominantly to channels which are closed or nearly closed, then they may be less broad. For example, a $q^2\bar{q}^2$-"state" coupled strongly to $\rho\rho$ and $\omega\omega$ may be rather narrow if its mass is below 1.5 mTeV.

The $\bar{p}p$-channel has several advantages in the study of the meson continuum in the 1-2 mTeV region. First, the threshold is immersed in the meson continuum, so it can be studied from annihilation at rest, which has many advantages (see below). Second, annihilation dominates the cross section until well above threshold. Third, there is no "spectator" nucleon as in conventional processes like $\pi N \rightarrow \pi\pi N$. This makes the partial wave analysis considerably simpler. Fourth, the atomic physics of the annihilation process can be used to constrain the quantum numbers of the $\bar{N}N$-system. Fifth, it is easy to draw natural-looking quark line diagrams leading to various exotic final states (see Fig. 3). If perhaps the $\bar{p}p \rightarrow ggg$ diagram looks unlikely, it is worth remembering that $\bar{p}p \rightarrow J/\psi$ proceeds via ggg-annihilation, and that Chanowitz has made a strong case that the $\iota(1440)$—a glueball candidate—was first observed in $\bar{p}p$-annihilation. [34]

The meson continuum appears to be dense with resonances in the 1-2 mTeV region. In inclusive processes such as $\bar{p}p \rightarrow \pi X$ interesting exotic states will likely be swamped by background from well known, strongly coupled states like f, A_2, D,... The same goes for exclusive final states such as $\bar{p}p \rightarrow \pi\pi\pi$, with resonant contributions from many well known $\pi\pi$-states: ρ, ε, f, g, ... To search for exotica it is necessary to filter. This can be done in two ways: First, the quantum numbers of the initial state can be constrained by selecting annihilations at rest from specific atomic configurations. Second, the quantum numbers of the final state can be restricted by studying specific, exclusive channels, primarily 3-body states in annihilation at rest and 2-body states in annihilation in flight.

Annihilation at rest occurs primarily from atomic s- or p-states. The $\bar{p}p$-atom starts in a quasiclassical orbit and cascades toward the ground state. The annihilation amplitude is so large that the annihilation width of the 2p-level is greater than its radiative width. Thus, in isolation (in practice, in a gas at not very high pressure) the annihilation is frequently from the

2p-state (55% at NTP).[35] The ASTERIX collaboration at LEAR[36] has shown that it is possible to isolate p-wave annihilation in gaseous H_2 (>95% at NTP) by triggering on annihilation in coincidence with the appropriate antiproton-atomic X-ray. In a liquid hydrogen target the Stark-effect due to ambiant fields generated by other hydrogen atoms mixes s- and p-states which enhances annihilation from the s-states. Thus annihilation at rest in liquid H_2 is dominantly s-wave (~100%, <1% p-wave).[36]

It is therefore possible to dial the quantum numbers of the initial state with considerable reliability:

s-state: $^1S_0$ (J^{PC}=0^{-+}, I^G=0^+ or 1^-), or

$^3S_1$ (J^{PC}=1^{--}, I^G=0^- or 1^+)

p-state: $^1P_1$ (1^{+-}), or

^3P_J (0^{++}, 1^{++}, 2^{++})

The most interesting constraints I know of come from the s-wave because the initial quantum numbers are most limited.

The potential of combining annihilation from a specific initial state with the selection provided by looking at a specific, exclusive final state is best illustrated by a few examples:

- Example 1: $\bar{p}p \to \pi^0\pi^0\eta$ [at rest in liquid H_2] This final state cannot couple to 1^{--}, so if the annihilation is from the s-wave of the $\bar{p}p$-atom, the $\pi^0\pi^0\eta$ system must have quantum numbers J^{PC}=0^{-+}, I^G=0^+ or 1^-. The allowed quantum numbers for the meson pairs in the final state are tabulated in Table VI. The Dalitz-plot for the $\pi^0\pi^0\eta$ system is shown schematically in Fig. 4. The interest in the channel stems from the appearance of the CP-exotic 1^{-+} quantum numbers. The $\ell \geq 2$ $\pi\pi$ or $\pi\eta$ isobars, f, f', A_2, etc. must be produced in a d-wave relative to the third meson and are likely to be suppressed. The δ(960) is narrow and easily distinguished from a (presumably higher mass) 1^{-+}-state. This leaves the $\pi^0\pi^0$ s-wave as the only important source of background which might mask a 1^{-+}-state. This channel generates a flat distribution over the Dalitz-plot, which should be possible to distinguish from the variation characteristic of the 1^{-+} channel.

Table VI

Two Meson States in $[\bar{p}p]_{s\text{-wave}} \rightarrow \pi^0\pi^0\eta$

Mesons	$J^{PC}I^G$	Angular momentum*	Known States
$\pi^0\eta$	$0^{++}1^-$	$\ell = 0$	$\delta(960)$
	$1^{-+}1^-$	$\ell = 1$	CP - exotic
	$2^{++}1^-$	$\ell = 2$	$A_2(1320)$
	$3^{-+}1^-$	$\ell = 3$	CP - exotic
	...		
$\pi^0\pi^0$	$0^{++}0^+$	$\ell = 0$	$\varepsilon(700)$, $\varepsilon(1300)$,...
	$2^{++}0^+$	$\ell = 2$	f(1270), f'(1525),...
	...		

*ℓ is the relative angular momentum of the third meson with respect to the other two.

Of course this experiment is not at easy as it may seem to a theorist: in particular, the $\pi^0\pi^0\eta$ final state is really a 6γ-state, which will require a detector with high quality photon identification and very good electromagnetic energy resolution. One might think that the $\pi^-\pi^+\eta$ channel would be easier to study experimentally. However this channel has a large background from isobars in the $(\pi\pi)$ $1^{--}1^+$ channel, which is rich in resonances—ρ,ρ'...—which are not flat across the Dalitz-plot. Annihilation in a gas target does not allow any new background channels. Its disadvantage seems to be that the signal ($1^{-+}1^+$) will be diluted because annihilation from most of the initial states yield only non-exotic spin parity. For example, the background channels $f\eta$ and $A_2\pi$ can be produced with ℓ=1 if the initial state is 1^{++} or 2^{++}. This will be a difficult but perhaps rewarding experiment. One wonders whether CP-exotics have resisted discovery all these years largely because of the obscurity of their decay channels and the trouble of finding them.

- Example 2: $\bar{p}p \rightarrow \pi^0\pi^0\phi$ [at rest in liquid] [$\bar{p}p \rightarrow \pi^0\eta\phi$ is similar] In this case the system can't couple to 0^{-+}, so if the annihilation is from the s-wave of the $\bar{p}p$-atom, the $\pi^0\pi^0\phi$ system has quantum numbers $J^{PC}=1^{--}$, $I^G=0^-$ or 1^+. $\phi\pi$ is an interesting channel. It has long been advocated as a $q^2\bar{q}^2$-channel since the quark content of a meson coupling strongly to $\phi\pi$ is $s\bar{s}(q\bar{q})^{I=1}$.[37] The only meson known to decay to $\phi\pi$ is the intriguing state at 1490 MeV seen at Serpukhov.[38] The quantum numbers of the $\phi\pi$-system produced via $\bar{p}p\rightarrow\pi^0\pi^0\phi$ [at rest in liquid] are given in Table VII:

Table VII

$\pi^0\phi$ states produced in $[\bar{p}p]_{s\text{-wave}}\rightarrow\pi^0\pi^0\phi$

Mesons	$J^{PC}I^G$	Angular momentum*	Known States
$\pi^0\phi$	$1^{+-}1^+$	$\ell=0$	–
	$0^{--}1^+$	$\ell=1$	CP - exotic
	$1^{--}1^+$	$\ell=1$	C(1490)[38]
	$2^{--}1^+$	$\ell=1$	–
	...		

*ℓ is the relative angular momentum of the third meson with respect to the other two.

The background to the interesting $\phi\pi^0$ signal comes once again from the $\pi^0\pi^0$-s-wave. Using $\pi^0\pi^0$ instead of $\pi^+\pi^-$ avoids a $\rho^0\phi$-background. The $\eta\phi$-channel is an interesting glueball channel with $I^G=0^-$ and $J^{PC}=1^{+-}, 0^{--}, 1^{--}, 2^{--}, \ldots$

More examples of interesting exclusive channels can be found in the "Crystal Barrel" proposal to LEAR[39], where many channels are discussed. Looking at Ref. [39] one sees several ambitious proposals to search for CP-exotics in high multiplicity exclusive final states. For example, they take up Isgur and Paton's suggestion[40] that CP-exotics may be found decaying into $D\pi$:

$$\bar{p}p\rightarrow\pi^{\pm}X^{\mp}$$
$$\quad\llcorner D^0\pi^{\mp}$$
$$\qquad\llcorner\pi^0\pi^0\eta$$

so, in all, $\bar{p}p\rightarrow\pi^{\pm}\pi^{\mp}\pi^0\pi^0\eta$, which is actually two pions and six gammas. There are many non-exotic modes of $\bar{p}p$-annihilation at rest which populate this final state, leading to a fierce combinatoric background: just consider the ordinary isobars which populate the same final state, eg. $\rho\rho\eta$, $\omega\delta$, $\rho\epsilon\eta$,... This problem is compounded by the small Q-value of the reaction (~315 MeV). The final state does not provide any useful filtration, in fact it makes things worse: If $X^{\pm}$ is CP-exotic (1^{-+})–which is the object of the search–then annihilation in liquid H_2 only produces $\pi^{\pm}X^{\mp}$ in the p-wave, which is further supressed by the low Q-value. Annihilation in gaseous H_2 allows the $\pi^{\pm}X^{\mp}$ s-wave but allows relatively more non-exotic background channels leading to the same final state. It seems to me one should stick to the simplest useful final states which are two stable mesons (π, η, K) (or a meson and a photon) recoiling against a third meson (or a photon). For a list of the quantum numbers available to two meson states see Table VIII.

The final subject I would like to discuss under the general heading of Voodoo QCD is the search for direct channel resonances in $\bar{p}p$-annihilation in flight. Many years ago Freund and Rosner gave a straightforward argument[33] based on duality that the existance of Regge exchange at in high energy $\bar{p}p$-scattering requires the existance of a tower of direct channel resonances in low energy $\bar{p}p$-annihilation. In QCD these resonances must be interpreted as two quark-two antiquark states, as can be seen from Fig. 5. There are many such states[41] because there are many ways to couple the spins, colors, flavors and orbital quantum numbers of four quarks. Also there are many active partial waves in $\bar{p}p$ even a short distance above threshold. So the spectrum of direct channel $\bar{p}p$-resonances should be dense. Furthermore, there is no reason to expect these resonances to be narrow. These are not the "narrow baryonium" states which caused much passing excitement in the 1970's; instead they are strongly coupled to the $\bar{p}p$-channel in exactly the same way the ordinary mesons (ρ, f, A_2,...) are strongly coupled to meson-meson scattering. Exotic color configurations like

$$[Q^2]^6[\bar{Q}^2]^{\bar{6}}$$

are no longer thought to be particularly stable[42] and don't appear to couple strongly to $\bar{p}p$ anyway. Finally, $q^2\bar{q}^2$-states at or below $\bar{p}p$-threshold have no angular momentum barrier to stabilize them. They are best thought of as part of the meson-meson continuum, which they influence in more subtle ways.[43]

Table VIII

Quantum numbers of two (narrow) meson systems

J^P \ I^G, C_n	$0^+, -$	$1^+, -$	$1^-, +$	$0^-, -$
0^+	$\pi^0\pi^0$, $\pi^+\pi^-$, $\eta\eta$ K_SK_S, $K\bar{K}$, $\phi\phi$	*	$\eta\pi^0$ K_SK_S, $K\bar{K}$	*
0^-	$\phi\phi$	$\phi\pi^{0*}$		$\phi\eta^*$
1^+	$\phi\phi$	$\phi\pi^0$		$\phi\eta$
1^-	$\phi\phi^*$	$\pi^+\pi^-$, $\phi\pi^0$ $K\bar{K}$	$\eta\pi^{0*}$	KK, $\phi\eta$
2^+	$\pi^0\pi^0$, $\pi^+\pi^-$, $\eta\eta$ K_SK_S, $K\bar{K}$, $\phi\phi$	$\phi\pi^{0*}$	$\eta\pi^0$ K_SK_S, $K\bar{K}$	$\phi\eta^*$
2^-	$\phi\phi$	$\phi\pi^0$		$\phi\eta$
3^+	$\phi\phi$	$\phi\pi^0$		$\phi\eta$
3^-	$\phi\phi^*$	$\pi^+\pi^-$, $\phi\pi^0$ $K\bar{K}$	$\eta\pi^{0*}$	KK, $\phi\eta$
4^+	$\pi^0\pi^0$, $\pi^+\pi^-$, $\eta\eta$ K_SK_S, $K\bar{K}$, $\phi\phi$	$\phi\pi^{0*}$	$\eta\pi^0$ K_SK_S, $K\bar{K}$	$\phi\eta^*$
4^-	$\phi\phi$	$\phi\pi^0$		$\phi\eta$

*CP-exotic channel

It seems that the challange to experimentalists is to sort out a rich mix of broad, overlapping resonances. Several attempts were made to attack this problem in the 1970's using two meson final states to select specific quantum numbers and using both angular distributions and polarization data to perform amplitude analyses.[44] The results of these studies are tantalizing [See Fig. 6]–clearly many partial waves are active in the region just above threshold–but the experiments were limited by their modest statistics and the groups looking at different final states (eg. $\pi^0\pi^0$, $\pi^+\pi^-$, $K\bar{K}$) never completely sorted out their differences. A dedicated program of study of $\bar{p}p \rightarrow M_1M_2$ at a high luminosity $\bar{p}p$-facility could make a major contribution to this subject by adroitly choosing meson-meson channels from the menu of Table VIII. Some of the states in Table VIII are particularly interesting because they select CP-exotics or glueballs. Notable examples are $\phi\phi$, $\phi\pi^0$, $\eta\pi^0$, and $\phi\eta$.

There is a potential problem with this program which must be addressed: Even if there were no true resonances in $\bar{p}p$ scattering, it is quite likely that the excitation function of each partial wave would rise and fall with energy in a way which imitates resonance behavior. This phenomenon goes by the name of "peripherality". The idea is this: $\bar{p}p \rightarrow M_1M_2$ is probably dominated by a particular impact parameter. Central collisions yield high multiplicity annihilation, while large impact parameter collisions yield little annihilation at all. So it is reasonable to suppose that low multiplicity annihilation comes dominantly from intermediate impact parameters, for example, $b \approx 1.4$fm. Then the excitation function of a given partial wave will peak at a center of mass momentum given by

$$k_{M_1M_2} \approx \frac{\ell}{b}$$

provided the center of mass momentum in the entrance channel ($\bar{p}p$) is not too different from that of the exit channel (M_1M_2). As can be seen from Fig. 7, this condition is satisfied for $\bar{p}p \rightarrow \pi\pi$ in the $J=\ell+1$ channel not far above threshold. It should be emphasised that the total cross section would be rather structureless while each partial wave turns on and fades away.

Fortunately there is a straightforward way to distinguish true resonant behavior from "peripherality": true resonances factorize–they appear at the same center of mass energy in all channels–even though they may be produced "peripherally", that is, the dominant resonances are those whose mass and angular momentum satisfy the condition $k \approx \ell/b$. Peripheral effects vary considerably with meson mass: a given partial wave peaks at a different E_{CM} for $\pi\pi$, $\eta\eta$, $K\bar{K}$, etc. So there is considerable motivation for a systematic study of the $\bar{p}p \rightarrow M_1M_2$ reaction as a function of energy and meson type.

References

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1. I. Hinchliffe, unpublished.
2. For a review, see J. W. Cronin, Rev. Mod. Phys. **53**, 373 (1981). See also the paper by L. Wolfenstein in these proceedings.
3. L. Wolfenstein, Phys. Rev. Lett. **13**, 569 (1964).
4. V. V. Barmin, et al., Nucl. Phys. **B247**, 293 (1984).
5. I thank L. B. Okun' for emphasizing this point to me.
6. J. Donoghue, these proceedings.
7. E. Gabathuler and P. Pavlopoulos, in *Proceedings of the Workshop on Physics at LEAR with Low Energy Cooled Antiprotons*, Erice 1982, U. Gastaldi and R. Klapisch eds. (Plenum Press, New York, 1982), p. 747.
8. Particle Data Group, Rev. Mod Phys. **56**, S1 (1984).
9. J. A. Christenson et al., Phys. Rev. Lett. **43**, 1209 (1979).
10. J. K. Black et al., Phys. Rev. Lett. **54**, 1628 (1985).
11. R. H. Bernstein et al., Phys. Rev. Lett. **54**, 1631 (1985).
12. L. Adiels et al., CERN Report CERN-EP/86-04, January 1986, presented at the Topical European Meeting on the Quark Structure of Matter, October, 1985.
13. N. W. Tanner and R. H. Dalitz, Oxford preprint, Ref. 2/86, to be published in Nuclear Physics.
14. N. W. Tanner, in Proceedings of the Third Lear Workshop, *Physics with Antiprotons at LEAR in the ACOL Era*, Tignes-Savoie, France, 1985, U. Gastaldi, R. Klapisch, J.-M. Richard, J. Tran Thanh Van, eds. (Editions Frontières, Paris, 1985), p. 483.
15. J. Bell and J. Steinberger, in *Proceedings of the Oxford International Conference on Elementary Particles*, Oxford, 1965, T. R. Walsh, R. G. Moorhouse and B. Southward, eds., (Rutherford High Energy Laboratory, Chilton, Didcot, 1966), p. 195.
16. P. K. Kabir, Phys. Rev. **D2**, 540 (1970).
17. C. Zemach, Phys. Rev. **133**, B1201 (1964); Ya. Zel'dovich, Yad. Fiz. **6**, 840 (1967), [Sov. J. Nucl. Phys. **6**, 611 (1968)].

18. L. F. Li and L. Wolfenstein, Phys. Rev. **D21**, 178 (1980).

19. M. Macri, in Proceedings of the Third Lear Workshop, *Physics with Antiprotons at LEAR in the ACOL Era*, Tignes-Savoie, France, 1985, U. Gastaldi, R. Klapisch, J.-M. Richard, J. Tran Thanh Van, eds. (Éditions Frontières, Paris, 1985), p. 423.

20. M. Poulet, *ibid.*, p.433.

21. W. Buchmüller, *ibid.*, p.327.

22. M. G. Olsson, *ibid.*, p. 341.

23. For further discussion see the talk by M. B. Olsson in these proceedings.

24. S. J. Brodsky and P. Lepage, Phys. Rev. **D24**, 2848 (1981).

25. C. Baglin et al. CERN report CERN-EP/85-01 (1985).

26. M. Macri, in Proceedings of the VII European Symposium on Antiproton Interactions, *Antiproton 1984*, Durham, England, 1984, M. R. Pennington, ed. (Adam Hilger, Bristol, 1985), p. 339.

27. J. E. Gaisser, SLAC report 255 (1982); M. Oreglia, SLAC report 236 (1980).

28. J. D. Bjorken, private communication.

29. R. L. Jaffe, K. Johnson and Z. Ryzak, Mit preprint MIT-CTP-1271, 1985 to be published in Ann. Phys. (N.Y.).

30. G. Binon et al., Nuovo Cim. **78A**, 313 (1983); Yad. Fiz. **38**, 934 (1983) [Sov. J. Nucl. Phys. **38**, 561 (1983)]; S. S. Gershtein, A. A. Likhoded and Yu. Prokoshkin, Z. Phys. **24C**, 805 (1984); Yad. Fiz. **39**, 251 (1984) [Sov. J. Nucl. Phys. **39**, 156 (1984)]; G. Binon, et al., Nuovo Cim. **80A**, 363 (1984).

31. K. Etkin et al., Phys. Rev. Lett. **49**, 1620 (1982).

32. M. Chanowitz and S. Sharpe, Nucl. Phys. **B222**, 211 (1983); T. Barnes and F. E. Close, Phys. Lett. **116B**, 365 (1983); T. Barnes, F. E. Close and F. de Viron, Nucl. Phys. **B224**, 241 (1983); B. M. Flensberg, C. Peterson and L. Sköld, Z. Phys. **C22**, 293 (1984); N. Isgur, R. Kokoski and J. Paton, Phys. Rev. Lett. **54**, 869 (1985).

33. J. Rosner, Phys. Rev. Lett. **22**, 689 (1969); H. J. Lipkin, Nucl. Phys. **B9**, 349 (1969); M. Jacob and J. Weyers, Nuovo Cim. **69A**, 521 (1970), **70A**, 285 (E) (1970).

34. M. Chanowitz, Phys. Rev. Lett. **46**, 981 (1981).

35. For a review of experiments see the paper by H. Poth in these proceedings.

36 ASTERIX Collaboration, Cern report, CERN-EP/84-85, 1984.

37. F. E. Close and H. J. Lipkin, Phys. Rev. Lett. **41**, 1263 (1978).

38. S. I. Bityukov et al., Pis'ma Zh. Eksp. Theor. Fiz. **42**, 310 (1985) [JETP Lett. **42**, 384 (1986)]; Yad. Fiz. **38**, 1205 (1983) [Sov. J. Nucl. Phys. **38**, 727 (1983)] I thank L. G. Lansberg for calling my attention to these references.

39. E. Aker et al., Crystal Barrel Proposal, CERN report, CERN/PSCC/85-56, October 1985.

40. N. Isgur and J. Paton, Phys. Rev. **D31** 2910 (1985).

41. R. L. Jaffe, Phys Rev. **D17**, 1444 (1978).

42. For a review of the dynamics of baryon-antibaryon resonances, see L. Montanet, G. C. Rossi and G. Veneziano, Phys. Rep. **63**, 149 (1980).

43. R. L. Jaffe and F. E. Low, Phys. Rev. **D19**, 2105 (1979).

44. A. A. Carter, et al., Phys. Lett. **67B**, 117, 122 (1977); A. A. Carter, Nucl. Phys. **B127**, 202 (1977); **B132**, 176 (1978); **B141**, 467 (1978); C. De Marzo et al., private communication from R. E. Lanou, D. C. Peaslee and L. Rosenson, quoted by L. Monanet in *Meson Spectroscopy 1977*, Proceedings of the Fifth Interantional Conference on Experimental Meson Spectroscopy (Boston, 1977).

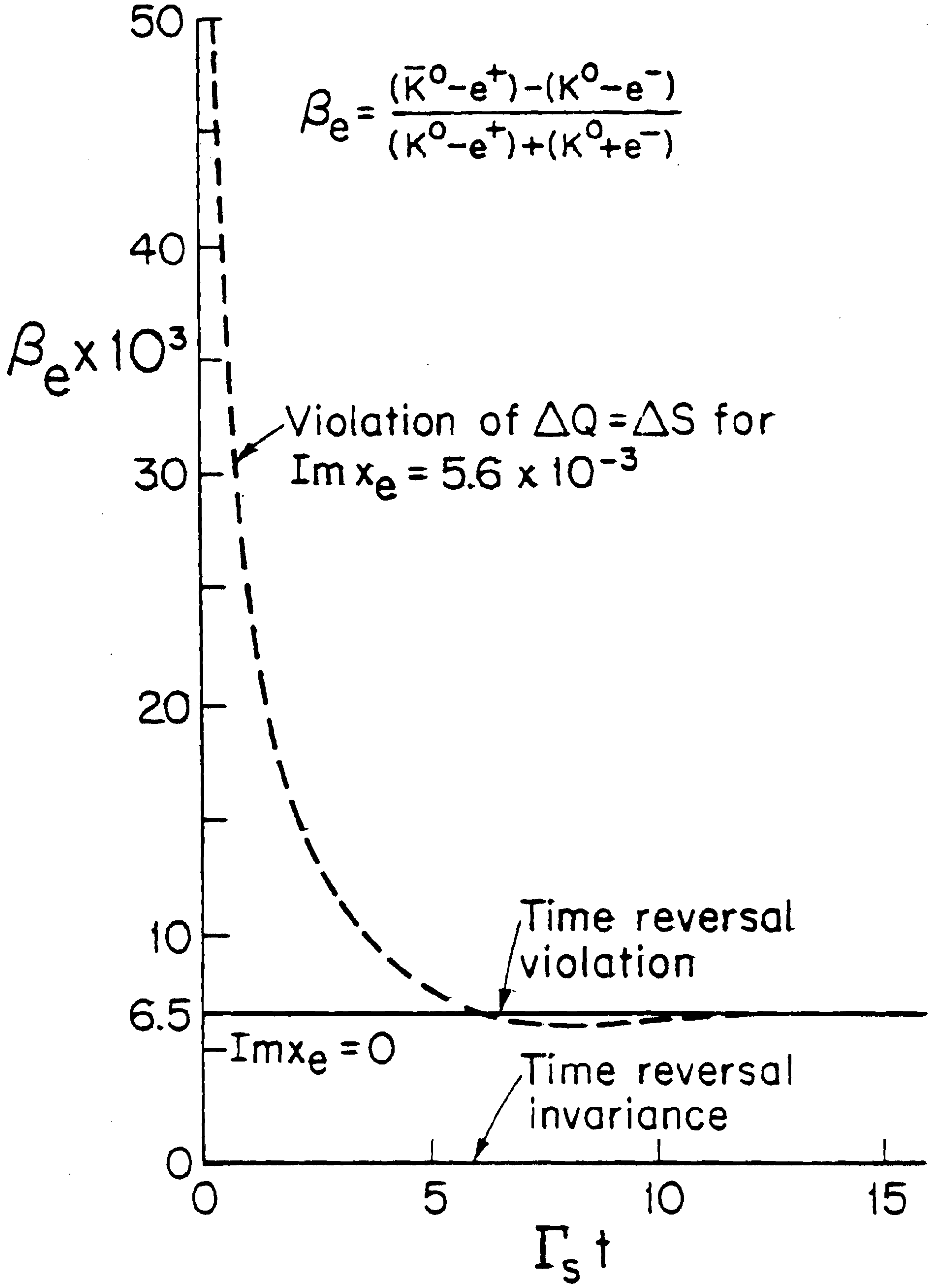


Figure 1. Signature for T-invariance violation or $\Delta S \neq \Delta Q$ in the experiment of Tanner, et al.[14]

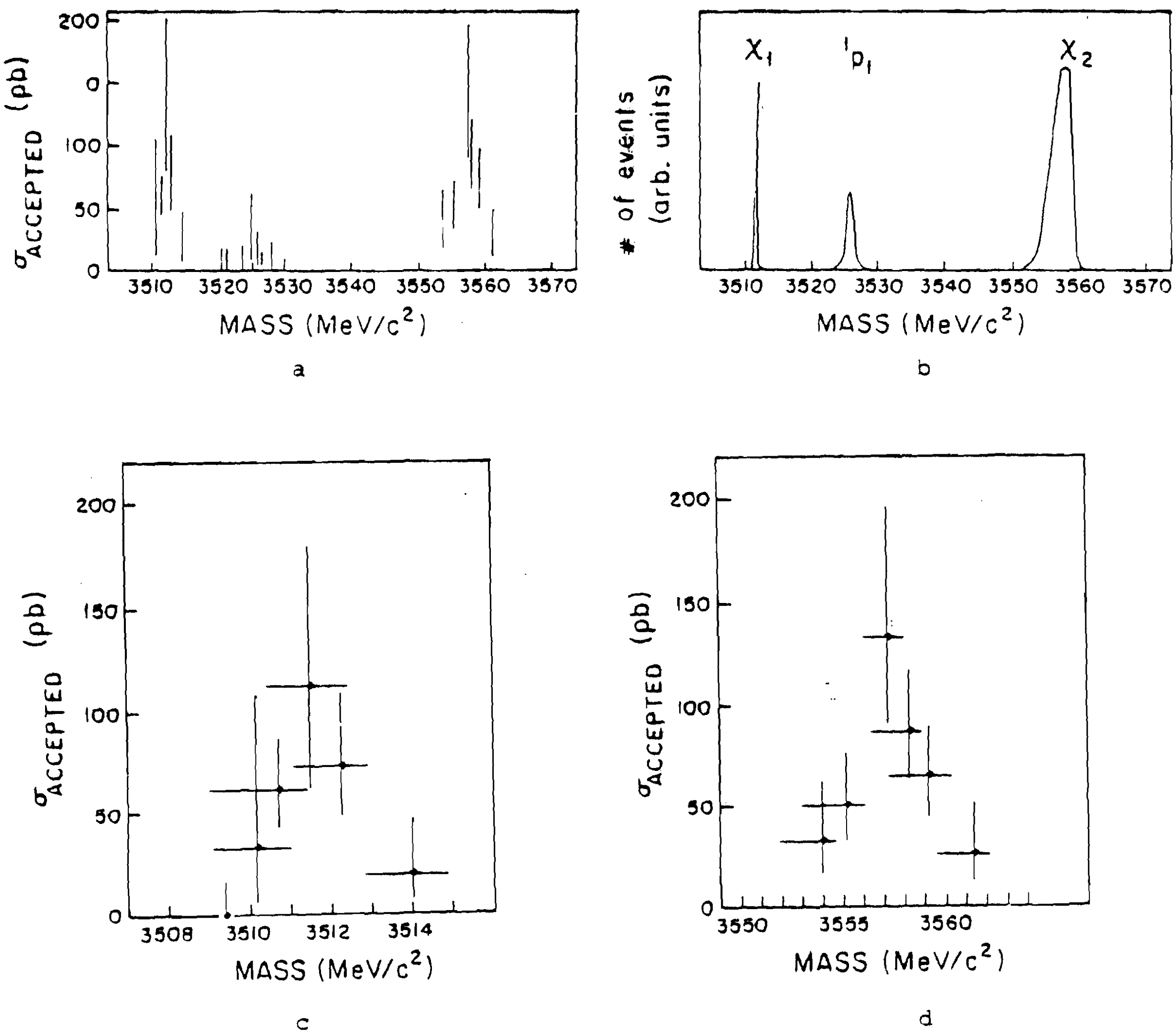


Figure 2. Results of ISR experiment R704.[19]

a) $\sigma[\bar{p}p \rightarrow J/\psi + \ldots]$;

b) anticipated signal at a new, high intensity $\bar{p}p$ - facility;

c) same as a) detail of χ_1 region;

d) same as a) detail of χ_2 region;

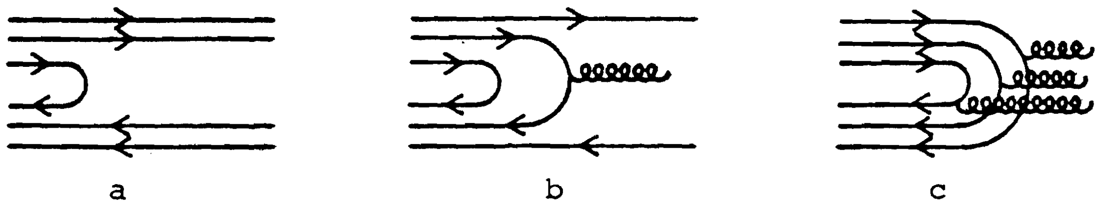


Figure 3. Quark production mechanisms for:
a) $\bar{p}p \rightarrow q^2\bar{q}^2$ b) $\bar{p}p \rightarrow q\bar{q}g$; c) $\bar{p}p \rightarrow$ glueball.

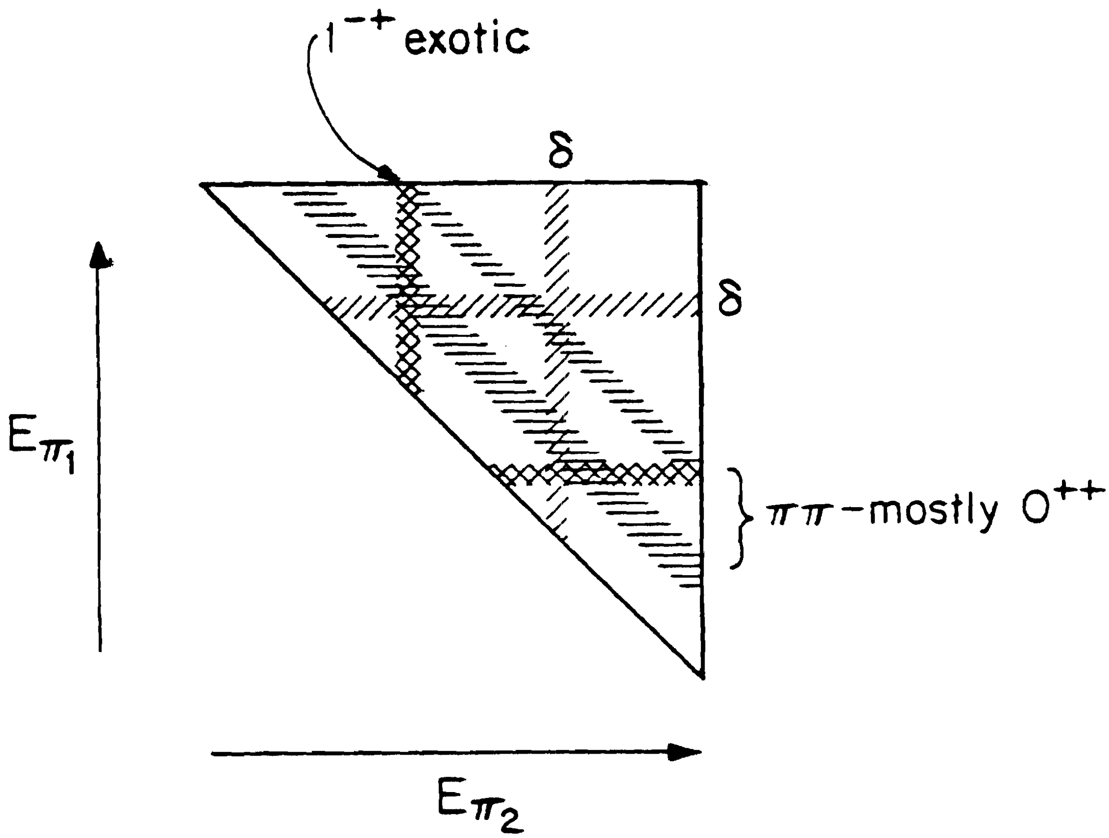


Figure 4: Dalitz plot for $\bar{p}p \rightarrow \pi^\circ\pi^\circ\eta$ (ignoring masses).

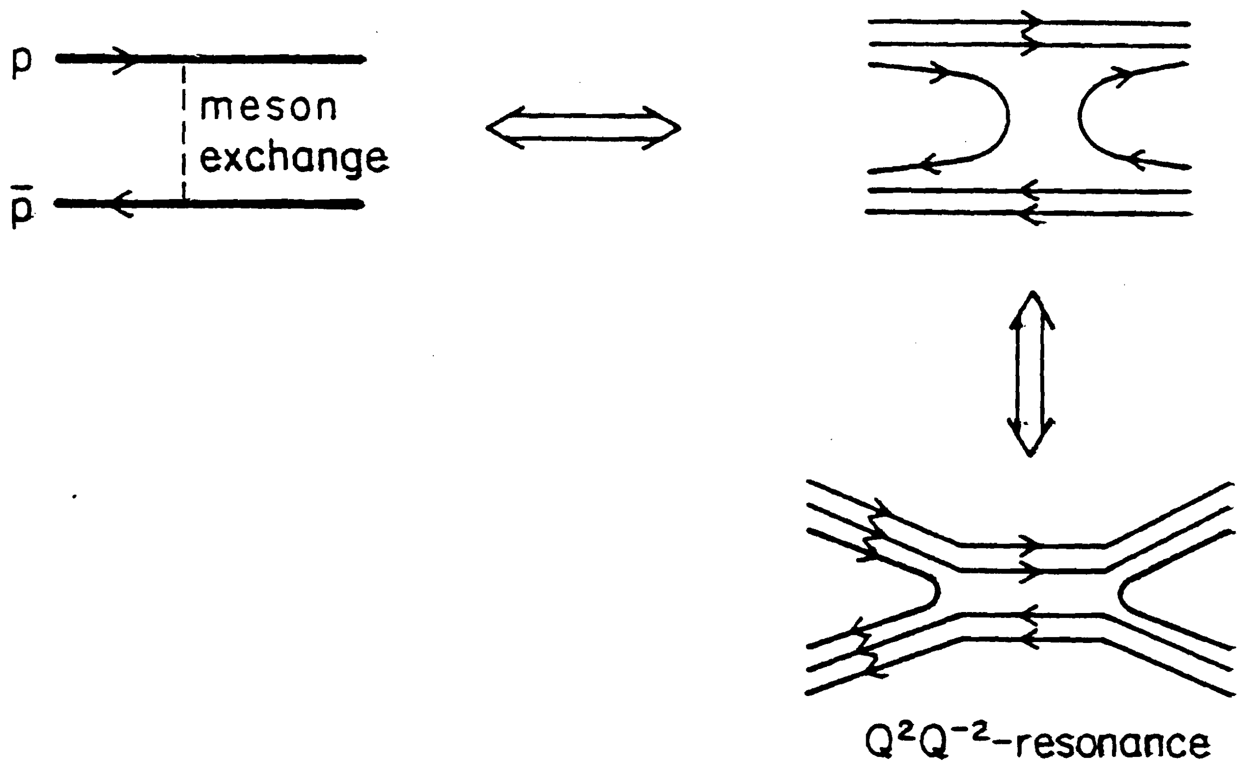
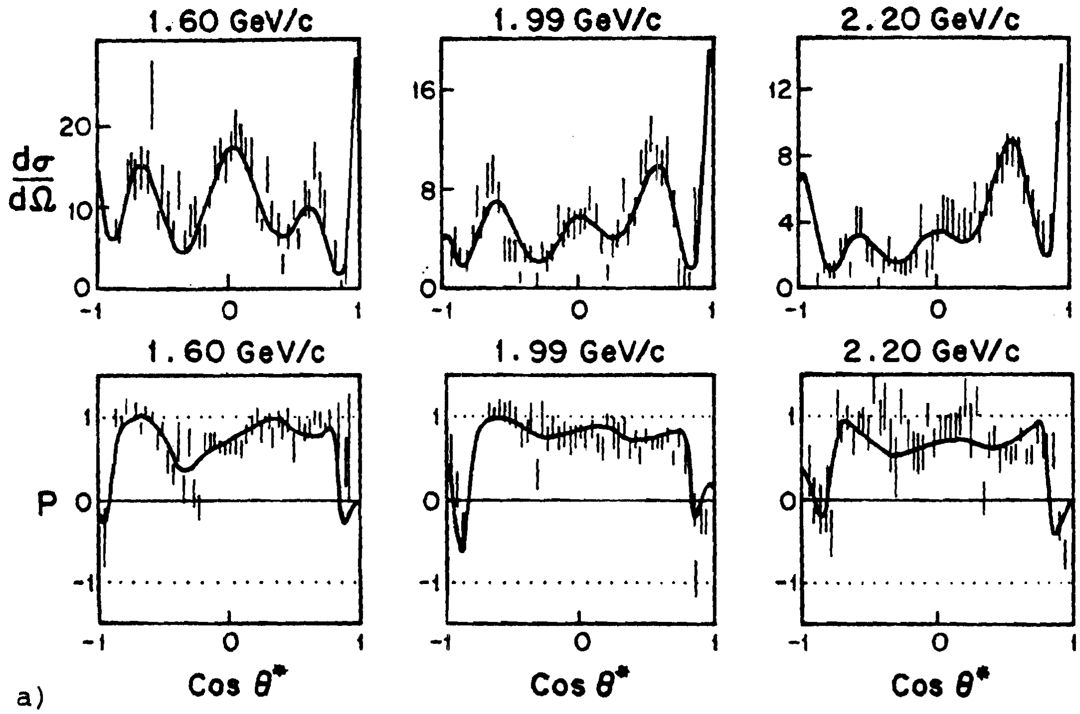
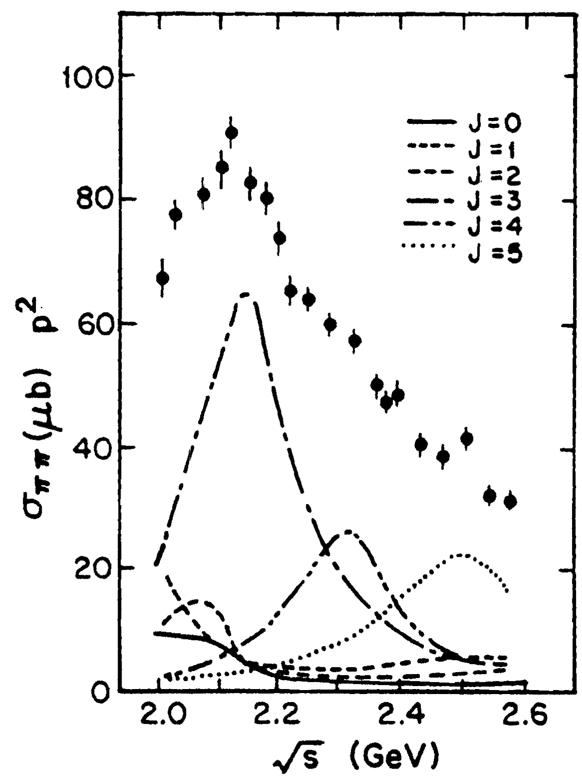


Figure 5. The duality argument for broad $q^2\bar{q}^2$ (typical hadronic) resonances in $\bar{p}p$-scattering.



a)



b)

Figure 6. a) Angular distribution and polarization in $\bar{p}p \to \pi^+\pi^-$ [44]; b) Total cross section for $\bar{p}p \to \pi\pi$;

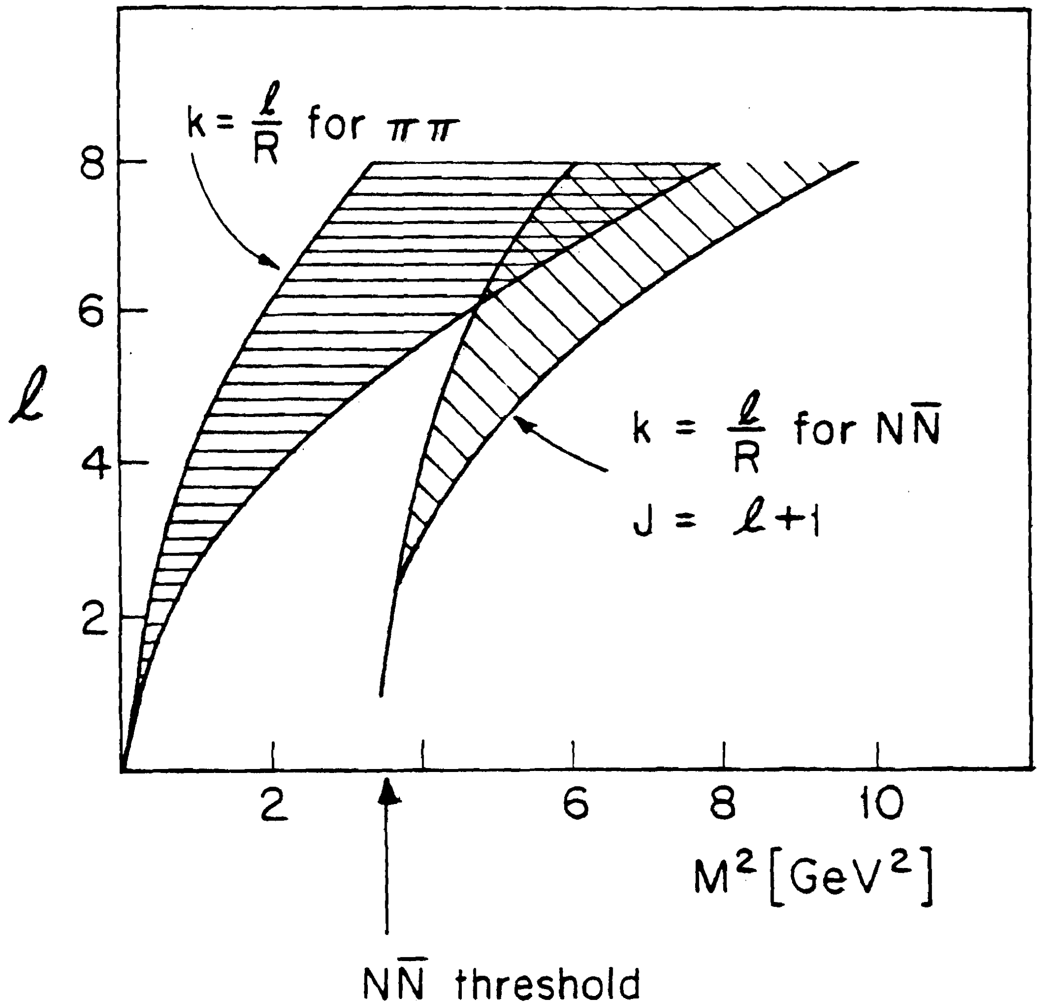


Figure 7: Peripherality: $k = \ell/b$ for $\pi\pi$ and $k = (J-1)/b$ for $N\bar{N}$ with $b = 1.4 \pm 0.3$ fm.