DELTA, IOTA AND OTHER MESON SPECTROSCOPIES

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Presented at
Antimatter Physics at Low Energy
Fermilab Low Energy Antiproton Facility Workshop

Summary/Abstract

This talk is given from the point of view of an experimentalist. Meson spectroscopy in the 1-3 GeV region is interesting because experiments exploring this region, in particular radiative psi decay, have found a rich structure of resonances too complicated to unravel with any one experiment, and not easily interpreted with any one theoretical model. None of the theoretical calculations predicting all kinds of interesting and exotic objects in this region is very convincing or reliable. Additional input from $\bar{p}p$ annihilation can be very useful in helping to find the answers to the following three interesting open questions:

1. What exactly is this spectrum? What are the masses and quantum numbers of the resonances, as determined from analysis of data without theoretical prejudices?
2. How is this spectrum described by QCD? Is there evidence for new kinds of states like glue-balls, hybrids, axions, Higgses or multiquark exotics?
3. Is there any evidence for new physics beyond QCD?

I. Introduction - Where is the Physics?

Hadron physics is very different from electroweak physics, where there has always been a standard model, and experiments either test reliable predictions or look for new physics beyond the standard model. Even though we now believe the correct theory for hadron physics to be QCD, nobody knows how to use QCD to calculate the meson spectrum. A collective effort by theorists and experimentalists is needed to explore this region, with experimental data guiding the theorists in constructing QCD-motivated models, and with the predictions of these models as guides to future experiments. A successful implementation of this program will at least teach us how to use QCD for hadron physics. It may also lead to the discovery of new types of hadrons suggested by QCD, like glue balls, hybrids or multiquark exotics. It may give us insight into the early universe or astrophysical puzzles like Cygnus-X3. It may even lead to evidence for new physics beyond the standard model.

It is interesting to look at Standard Model Physics and Hadron Physics with a "burger model". These days in America everything has been burgerized. There are beefburgers, fishburgers, pizzaburgers, shrimpburgers, etc. etc. Even the U.S. Supreme Court has been burgerized, with Chief Justice Earl Warren replaced by Warrenburger. Fast-Food outfits have put so much other junk into their burgers that one very popular TV commercial showed a lady asking "Where's the beef?" This tradition has been followed by the Fast-Physics calculators, who have put so much other junk into their physicsburgers that one can ask "Where's the physics?".

There are two kinds of physicsburgers. The electroweak burger has a thick slice of solid predictions on a base of a well defined standard model, covered with a reliable calculation, and garnished with data, Monte Carlo, computer programs and χ^2 fits. The physics is clear. The hadron burger has a base of ad hoc assumptions, covered with free parameters and nothing else and garnished with "reliable" data, Monte Carlo, computer programs and χ^2 fits. There is usually a nearby waste basket filled with rejected "unreliable" data. One can well ask "Where is the physics?"

There are two approaches to using QCD for hadron physics: the southern fundamentalist approach and the northern iconoclastic approach.

The fundamentalists believe that "In the beginning God created the Bag", and follow the implications of the Bag with religious fervor, using religious terms like voodoo QCD. The lunatic fringe of the fundamentalists believe that the "n" in Big Bang cosmology is a typographical error and that all multiquark physics is describable with a Big Bag. They lose all contact with the real world as they follow their religion and send experimentalists on wild goose chases for nonexistent objects like narrow baryonium states.

The iconoclasts are atheists (or asakists - from the Greek ΣAKKOΣ) who refuse to believe anything and are always looking for alternative models in case their favorite model is wrong. Even when they have invented the great standard model for which they eventually get the Nobel Prize, they do not browbeat experimentalists into looking for the phenomena predicted by their model, like charm and weak strangeness-conserving neutral currents. Instead they produce a plethora of alternative models with five quarks, six quarks, eight quarks, new unobserved heavy leptons, etc. to explain all possible disagreements of their right standard model with wrong experiments.

North and south in this context refer of course to locations of the two great centers of particle physics on Massachusetts Avenue, Harvard and M.I.T. (Nit-picking purists may point out that they are really Northwest and Southeast). The correct approach for experimentalists is to recognize that all these diverse types of theorists contribute to our understanding of physics. It is good that we have them, rather than one party line. But just as any good experimenter is very careful to look for all kinds of biases and acceptance criteria before drawing conclusions from a particular set of experimental data, he should also be aware of all the biases and acceptance criteria that go into any theoretical paper before drawing conclusions from their predictions. The key question is "Where is the physics?"

Two examples of these two approaches are the H-dibaryon predicted by Jaffe[1] (M.I.T.) and the prediction of the Λ magnetic moment by DeRujula et al (Harvard).

Jaffe's six-quark-bag calculation predicted the existence of the H and estimated its mass. Where is the physics? Solid general QCD-symmetry arguments show that the H should be the most stable dibaryon. The mass prediction clearly does not include all the right physics. Any bound state near the Λ-Λ threshold must have a Λ-Λ piece in its wave function that decreases exponentially and continues well outside the boundary of any bag. This has been pointed out by Jaffe, but overlooked by others who use his result. This exponential tail reduces the kinetic energy and lowers the mass. Experimental seaches for the H should have high priority, but no mass prediction should be taken seriously unless it manifestly contains all the right physics. For example, any calculation which says that the lowest dibaryon state with the H quantum numbers has a mass greater than the mass of two Λ's must be missing some physics.

DeRujula et al predicted the Λ magnetic moment by using the Δ-nucleon and Σ^*-Σ splittings to estimate flavor-SU(3) symmetry breaking and predicted $\mu\Lambda =$ -0.61 n.m. This was later confirmed with surprising precision by experiment which found exactly the same value, $\mu_\Lambda = -0.61$ n.m.,

Where is the physics? It is in the natural assumptions that (1) The Λ moment is entirely due to the strange quark. (2) The SU(3) prediction, $\mu_\Lambda = -(1/3)\ \mu_p$, must be multiplied by the ratio of the strange quark moment to the down quark moment. (3) Hyperfine splittings are due to "color-magnetic" quark-quark interactions which are proportional to the product of quark "color-magnetic moments". (4) The electromagnetic magnetic moments of the quarks are proportional to the color magnetic moments; thus the ratio of the strange quark moment to the down quark moment is given by the ratio of the Σ^*-Σ and Δ-nucleon mass splittings.

That's it. No Monte Carlos. No χ^2 fits. Just physics. Put in the physics; get out numbers.

Later I assumed quark magnetic moments are Dirac moments with a scale determined by some effective quark mass,[3] used the Λ-nucleon mass difference as the mass difference between the strange and nonstrange quarks,[4,5] and obtained a completely different prediction for μ_Λ which gave exactly the same value, $\mu_\Lambda = -0.61$ n.m.

The physics input here is that the same "effective quark mass" which may include all kinds of complicated quark-gluon interactions appears both in the quark magnetic moment and in the hadron masses. Why this should be so is an open question, left to be solved by QCD theorists. But the simple constituent quark model, with its manifestly simple physics, appears here as a bridge between the experimental data and the fundamental QCD description.

II. Examples of Successful Uses of Antiprotons in Hadron Physics

Low energy antiprotons can give valuable additional information on the way QCD works to make hadrons out of quarks and gluons. There is already a history of successful use of low energy antiprotons in hadron physics. The ω meson was one of the first resonances to be discovered and was first found in annihilation. Another interesting result from antiproton annihilation was the observed annihilation into kaon pairs, which dealt a death blow to the now-forgotten Fermi-Yang-Sakata model.[6] In this extension of the old Fermi-Yang model of the pion as a nucleon-antinucleon pair the nucleon and Λ are elementary particles classified in a fundamental triplet of SU(3) with the SU(3) quantum numbers which we now attribute to the quarks, and kaons are $\bar{\Lambda}$-N pairs.

The Sakata model forbids $\bar{p}p$ annihilation into K_L-K_S pairs, while annihilation into charged kaon pairs and charged pion pairs is allowed. This selection rule is an SU(3) rotation of the well-known selection rule forbidding the 2π decay of the ϕ meson, while allowing the dominant $K\bar{K}$ decay mode. The 2π decay mode is doubly forbidden, both by the OZI rule and by G-parity, and can go only by an OZI-violating diagram which also violates G-parity. In the quark model, an SU(3) rotation which interchanges s and u quarks interchanges the ϕ with a $(u\bar{u})$ state and interchanges charged pions and neutral kaons to give the selection rule:

$$(u\bar{u}) \rightarrow K_L\ K_S \text{ (forbidden)};\quad \pi^+\pi^- \text{ and } K^+K^- \text{ (allowed)} \tag{1}$$

This selection rule follows from both the OZI rule and the analog of G-parity based on the U-spin subgroup of SU(3) instead of isospin. Thus in the Sakata model, where the proton plays the role of the u-quark, the above selection rule holds for $\bar{p}p$ annihilation. This prediction was in strong disagreement with experiment, which showed that K_L-K_S pairs were produced at comparable rates with charged kaon and pion pairs.

If the proton is not elementary and is in a flavor SU(3) octet, the annihilation into K_LK_S is not forbidden by OZI nor SU(3). Thus the observed K_LK_S annihilation was one of the first indications that the proton was not elementary but had a composite structure.

III. Experimental Puzzles in the Meson Spectrum

Low energy antiprotons can give valuable additional information on the meson spectrum in the 1-3 GeV region, because two important characteristic features of the nucleon-antinucleon channel make it a natural complement to radiative ψ decay for exploring this spectrum.

1. The initial state contains only nonstrange quarks. Thus the production of "strangeonium" states should be forbidden by OZI. This contrasts with radiative ψ decay, where the final meson is produced by pair creation and is flavor independent except for mass factors.
2. As in radiative ψ decay, the final state of annihilation involves only mesons, with no spectator baryon. In annihilation at rest, initial states with well defined quantum numbers can be selected, thus greatly simplifying the analysis of the final state.

We first note the following experimental puzzles which have arisen from the presently available data on the meson spectrum.

3.1. The nature of the δ

The coupling of the δ to the $K\bar{K}$ channel is confused by the fact that the mass of the δ is below the $K\bar{K}$ threshold. Clarification of the relative strengths of the $\eta\pi$ and $K\bar{K}$ couplings is of interest in order to distinguish between two competing models for the δ as either a normal quarkonium state or as a $K\bar{K}$ "molecular" bound state.[7,8] This is also of interest in unraveling the nature of other states, like the iota, which appear to decay into states involving the δ but choose one of the decay modes of the δ and not the other. There are reports that the δ has been seen at LEAR in $\bar{p}p$ annihilation into the $\eta\pi\pi$ final state. Useful information would be obtained in looking for the δ in quasi-two-body final states recoiling against the η, ρ, ω, ϕ, etc. as well as the pion, and looking at the K_SK_S decay mode as well as $\eta\pi$.

$$\bar{p}p \rightarrow M\phi \rightarrow M\eta\pi \tag{2a}$$

$$\bar{p}p \rightarrow M\phi \rightarrow MK\bar{K}, \tag{2b}$$

where M denotes any meson state.

3.2. The nature of the iota and confusion with the E

The iota produced in radiative ψ decay is confusing in itself without recourse to theoretical models, because it appears to want to decay only into the $K\bar{K}$ decay mode of the δ and not the dominant $\eta\pi$ mode. The nature of the iota is further confused by results of other experiments, in particular the production of a state in this mass region with apparently the same quantum numbers, sometimes called the E, in $\bar{p}p$ annihilation, pion-nucleon peripheral reactions[9] and the decay[10] $\psi \rightarrow \omega\iota$, but with sufficiently different properties like mass and width to suggest that there may be two pseudoscalar states very close together in mass.[11] In this case both states are very likely produced in any given reaction, and the two can be produced with different strengths and relative phases in different reactions. A high statistics study of quasi-two-body $\bar{p}p$ annihilations in this mass region, with the iota recoiling against the π, η, ρ, ω, ϕ, etc. and looking at all decay modes could help unscramble this puzzle.

$$\bar{p}p \rightarrow M\iota \rightarrow M\eta\pi\pi \tag{3a}$$

$$\bar{p}p \rightarrow M\iota \rightarrow MK\bar{K}\pi, \tag{3b}$$

where M denotes any meson or two-meson state. Note that if M is nonstrange, the production of a strangeonium state would be forbidden by the OZI rule, and that the same is true for the production in pion nucleon peripheral reactions and the decay $\psi \rightarrow \omega\iota$. If the iota spectrum appears to be the same in all these reactions and differs from that observed in radiative ψ decay, this suggests that there are two states, one of which is strangeonium, and that there may be mixing between the two states. This point is discussed in more detail below.

3.3. Possible $\phi\phi$ resonances

The puzzling $\phi\phi$ states observed in pion-nucleon reactions have been suggested as candidates for tensor meson glueballs.[12] If these states are real resonances they are interesting regardless of which model describes them, since a normal quarkonium state produced in reactions with only nonstrange hadrons would not be expected to decay strongly to $\phi\phi$. It is therefore of interest to verify the existence of these resonances by looking in other channels and looking for other decay modes. A $\phi\phi$ search can be conducted both by formation and production:

$$\bar{p}p \rightarrow \phi\phi \tag{4a}$$

$$\bar{p}p \rightarrow M\phi\phi, \tag{4b}$$

where M denotes any meson state. The case where M is a pion is related by crossing to the pion-nucleon reaction where these resonances were observed, and should be a good candidate for seeing them again.[12]

3.4 θ, χ and all that

Other mesons seen in radiative ψ decays which are possible candidates for glue balls can also be searched for in $\bar{p}p$ annihilation. Here again strangeonium states should not be strongly produced, except in pairs as in the reactions (4).

IV. The pseudoscalar spectrum

Despite the continuing pressure by theorists to force the two lowest pseudoscalar mesons into a nonet, experiments continue to indicate that the η and η' mesons are not simple mixtures of the ground state strange and nonstrange configurations.[13-16] Quark model sum rules which disagreed strongly with experiment suggested that the η wave function was well represented by the standard nonet model , but that the η' was very different and had an additional component mixed into its wave function.[17,18] This has been confirmed by subsequent experiments on η and η' production in pion-nucleon reactions and most recently by the vector-pseudoscalar decays of the J/ψ involving the η and η'.

A simple test of the nonet mixing assumption which determines the mixing angle was originally suggested by Okubo.[19] The ratio of η and η' production in all reactions involving only nonstrange particles should be a universal constant independent of momentum transfer depending only upon the relative amounts of the nonstrange component in the wave functions of the two states; e.g.

$$\frac{\langle \eta\ \pi|T|\bar{p}p\rangle}{\langle \eta'\ \pi|T|\bar{p}p\rangle} = \frac{\langle \eta\ \pi\pi|T|p\bar{p}\rangle}{\langle \eta'\ \pi\pi|T|pp\rangle} = \frac{\langle \eta\ n|T|\pi^- p\rangle}{\langle \eta'\, n|T|\pi^- p\rangle} = \frac{\langle \eta\ \omega|T|\psi\rangle}{\langle \eta'\ \omega|T|\psi\rangle}\ . \tag{5}$$

This relation is manifestly violated.[13-16]

An alternative mixing scheme originally developed to treat the discrepancy with the quark model sum rules considers the mixing of the ground state and radially excited configurations.[18,20] The basic physics behind this model comes from the assumption that flavor mixing between $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$

quarkonium states results from an interaction in which a quark-antiquark pair of one flavor is annihilated and a pair with a different flavor is created. The mass operator for the quarkonium states in the light quark sector can be written

$$M = M^o + A \tag{6}$$

where M^o contains all the dynamics except the flavor mixing and involves a potential analogous to the potentials which fit the charmonium spectrum and hopefully come from QCD. The pseudoscalar eigenstates of Mo are the ground and radially excited states with a given flavor. Let η_f, η'_f and η''_f denote the ground, first radially excited and second radially excited states of a quark-antiquark pair with flavor f analogous to the notation η_c, η'_c and η''_c used for charmonium. The isoscalar states in the u and d flavor sector are denoted by η_n, η'_n and η''_n, e.g.

$$|\eta_n\rangle = \frac{1}{\sqrt{2}} \{|\eta_u\rangle + |\eta_d\rangle\} .$$

First order perturbation theory gives the pseudoscalar eigenstates, denoted by $|P\rangle$ in terms of the eigenfunctions of M^o denoted by P_i with unperturbed mass M_i as

$$|P\rangle = |P^0\rangle + \sum_i \frac{\langle P_i|A|P^0\rangle}{M_o - M_i} |P_i\rangle \tag{7}$$

Nonet mixing follows from the assumption that the matrix elements of A are very strong within the same nonet and small between different nonets. However, if the annihilation is a short range interaction insensitive to the number of nodes in the wave function, the matrix elements between states in different nonets should not be qualitatively smaller than those within a nonet. In this case the amount of mixing of any given state is primarily determined by the energy or mass denominator, and results in "nearest neighbor mixing". Since isospin is a good symmetry, we immediately see that the $u\bar{u}$ and $d\bar{d}$ states are nearly degenerate eigenfunctions of M^0, and any interaction which removes this degeneracy will mix the states into isospin eigenstates. The isovector states, the pion and its radial excitations, thus separate out and do not mix with the isoscalar states. We are left with considering the mixing of the strange and nonstrange isoscalar states.

Nearest neighbor mixing gives the same results as the standard nonet mixing for the η but mixes a radially excited nonstrange state into the η' with a destructive interference that reduces its radiative ψ decay. This radial mixing was originally introduced[17,18] to explain the anomalously low production of the η' observed in hadronic experiments,[13-16] which violates predictions based on the standard nonet mixing model. The next state above the η and η' is primarily a mixture of the first radially excited strange and nonstrange configurations with a negative phase and can be identified with the $\eta(1275)$. If it is nearly an SU(3) octet it will not be observed in radiative ψ decays at all.

The fourth and fifth unperturbed pseudoscalar states are the first radially excited strange pseudoscalar and the *second* radially excited nonstrange pseudoscalar. If these two states are nearly degenerate before mixing the eigenstates of the mass matrix are mixtures of these two states, which we denote by $|\iota\rangle$ and $|E\rangle$

$$|\iota\rangle = \cos\theta|\eta'_s\rangle + \sin\theta|\eta''_n\rangle \tag{8a}$$

$$|E\rangle = -\sin\theta|\eta'_s\rangle + \cos\theta|\eta''_n\rangle \tag{8b}$$

where θ is a mixing angle to be determined by the dynamics.

The near degeneracy of the two unperturbed states η'_s and η''_n follows from estimates of the excitation energies of these states above the first radially excited nonstrange state η'_n. Using the experimental charmonium spectrum to estimate radial excitation energies gives[20]

$$M^0(\eta''_n) - M^0(\eta'_n) \cong M(\psi'') - M(\psi') = 344 \text{ MeV} \tag{9a}$$

where M^0 denotes the unperturbed mass in the absence of mixing.

$$M^0(\eta'_s) - M^0(\eta'_n) \cong 2(m_s - m_u) \cong 2[M(\Lambda) - M(p)] = 355 \text{ MeV} \tag{9b}$$

where m_s and m_u denote the quark masses and the standard constituent quark model[2] is used to relate these to baryon masses[4,5]. Thus

$$M^0(\eta''_n) - M^0(\eta'_s) \cong -11 \text{ MeV} \cong 0 . \tag{9c}$$

The transition matrix elements for the production of these states in pion-induced hadronic reactions, where both states $|\iota\rangle$ and $|E\rangle$ should be produced via the nonstrange component in the wave function, are then

$$\langle \iota n|T|\pi^- p\rangle = \sin\theta\langle \eta''_n n|T|\pi^- p\rangle \qquad (10a)$$

$$\langle En|T|\pi^- p\rangle = \cos\theta\langle \eta''_n n|T|\pi^- p\rangle \ . \qquad (10b)$$

The reactions $\bar{p}p \to \iota\pi$, $\bar{p}p \to E\pi$, $\bar{p}p \to \iota\pi\pi$, $\bar{p}p \to E\pi\pi$ and the decays $\iota \to \rho\gamma$, $E \to \rho\gamma$, $\psi \to \omega\iota$ and $\psi \to \omega E$ should also proceed via the nonstrange component. Thus the transition matrix elements for these processes should satisfy the relation[11]

$$\frac{\langle \iota\pi|T|p\bar{p}\rangle}{\langle E\pi|T|\bar{p}p\rangle} = \frac{\langle \iota\pi\pi|T|p\bar{p}\rangle}{\langle E\pi\pi|T|pp\rangle} = \frac{\langle \iota n|T|\pi^- p\rangle}{\langle En|T|\pi^- p\rangle} = \frac{\langle \rho\gamma|T|\iota\rangle}{\langle \rho\gamma|T|E\rangle} = \frac{\langle \iota\omega|T|\psi\rangle}{\langle E\omega|T|\psi\rangle} = \tan\theta \ . \qquad (10c)$$

This relation has interesting experimental consequences. If there are indeed two and only two states at the iota with one unperturbed state purely strange, then independent of the mixing the same linear combination of the two mass eigenstates is produced in all processes like (10) involving no strange hadrons. The spectrum observed in the iota region should then be the same for all these processes, while a completely different spectrum can be observed in radiative ψ decays. This holds for all values of the mixing angle, and is independent of the nature of the nonstrange state responsible for the transitions (10). The relations (10) would still hold, for example, independent of mixing in the completely different case where the two unperturbed states before mixing are a purely strange quarkonium and a glueball and there is no nonstrange quarkonium state present in this mass region.

Since this model assumes that only two quarkonium states are mixed in the pseudoscalar spectrum observed near the iota, these tests can provide useful information on the possible presence of glueballs. These results would no longer hold if a glueball state is also present in addition to a nonstrange quarkonium state, with or without mixing.

V. Conclusions

There is much interesting hadron physics in the 1-3 GeV region which can be illuminated by experiments with low energy antiprotons.

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