BNL-42268

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BNL--42268

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December 19, 1988

Paper Presented by S.J. Lindenbaum at the
1988 BNL WORKSHOP ON GLUEBALLS, HYBRIDS AND EXOTIC HADRONS
Brookhaven National Laboratory
August 29-September 1, 1988

† Research carried out under the auspices of the U.S. Department of Energy under Contract Nos. DE-AC02-76CH00016 (BNL) and DE-AC02-83ER40107 (CCNY).

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ABSTRACT

In this paper we discuss the striking evidence obtained by BNL/CCNY[1-2] for the $g_T(2010)$, $g_{T'}(2300)$ and $g_{T''}(2340)$ $I^G J^{PC} = 0^+2^{++}$ resonances which comprise virtually all of the $\pi^- p \rightarrow \phi\phi n$. The complete breakdown of the expected OZI suppression, and the striking differences of these states from conventional states and background in other channels has so far only been successfully explained by assuming they are produced by 1-3 2^{++} glueballs. The comparison with J/ψ radiative decay results is made. A discussion of other glueball candidates in the light of a coupled channel analysis of the 2^{++} and 0^{++} channels is also made. The forthcoming search for an exotic J^{PC} glueball is discussed.

INTRODUCTION AND GENERAL INTERPRETATION

QCD has glueballs embedded in its guts since locally gauge invariant $SU(3)_{color}$ (without quarks) would have glueballs as the only hadrons in the world. The addition of quarks can in no way remove the glueballs. However the Particle Data Group Table has lots of $q\bar{q}$ states including several nonets of (uds) quarks but no glueball section. This indicates that glueballs are suppressed, or not recognizeable in the usual OZI-allowed (quark dominated) production. If at least one glueball is not established in our opinion QCD will become just another failed theory in the strong coupling non-perturbative region.

Since 1978[1-2] BNL/CCNY have used the OZI-forbidden reaction $\pi^- p \rightarrow \phi\phi n$ reasoning the pure glue intermediate state would resonate for glueballs (see Fig. 1a) while suppressing $q\bar{q}$ states etc. Thus this reaction would act as a very selective filter which readily passes glueballs (if they exist) while strongly rejecting $q\bar{q}$ states and thus provide an excellent vehicle for detecting and establishing glueball states. In strong interactions where there are so many possibilities of explanation due to the strong coupling, one has traditionally needed very striking and unusual characteristics of the data which forces you to accept a new phenomenon in order to establish it. This was true for Δ, J/ψ, Υ, etc.

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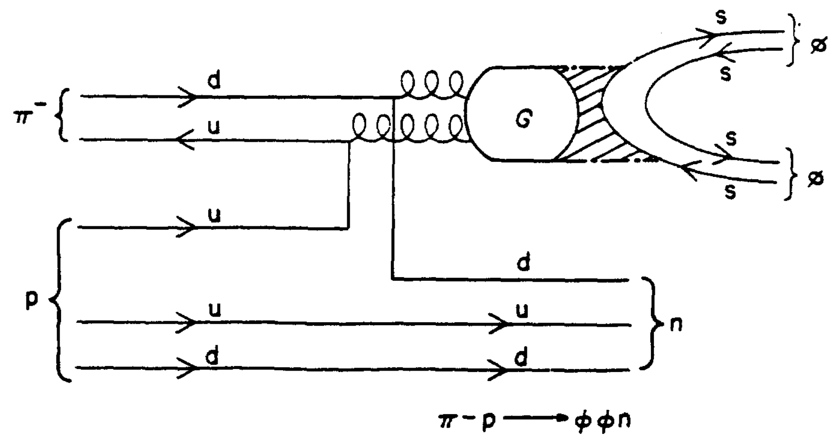

Figure 1a: $\pi^-p \to Gn \to \phi\phi n$ Quark Line Diagram

In a partial wave analysis and unitary K-matrix fit to these results we have found three [g_T, $g_{T'}$, $g_{T''}$][2-3] relatively very high cross section Breit-Wigner resonances in the $\phi\phi$ with $I^GJ^{PC} = 0^+2^{++}$ which completely break down the OZI suppression and no continuium or other states (within errors). They tower (by a factor ~ 50) over the ϕK^+K^- from the $\pi^-p \to \phi K^+K^-n$ OZI-allowed physical reaction which has mostly a featureless background and no evidence for any particular resonances. They also tower over the $K^+K^-K^+K^-$ from the OZI-allowed physical reaction $\pi^-p \to K^+K^-K^+K^-n$ by a factor ~ 1,000 which again appears to be featureless. The production mechanism is π-exchange ($\pi^+\pi^-$ annihilation). There is no indication whatsoever of the h(2030) ($I^GJ^{PC} = 0^+4^{++}$) [new name f_4(2030)] which should be strongly produced in π-exchange thus showing how good the OZI filtering action of this channel is against $q\bar{q}$ states composed of $u\bar{u}$ and $d\bar{d}$. This is consistent with what one would expect from the reaction shown in Fig. 1a. In contrast in $\pi^-p \to \phi K^+K^-n$ (Fig. 1b) where the K^+K^- pair is just above the ϕ in mass so that the kinematics etc. are very similar we find for the ϕK^+K^- ≈ 67% is structureless (flat background), ≈ 30% is 1^{--} (a kinematic effect for an s-wave ϕK^+K^- system produced by π-exchange), and only 3% is $J^{PC} = 2^{++}$ which appears different and non-resonant. Also in $\pi^-p \to K^0_SK^0_Sn$ in the region of the g_T resonances[4] we find a structureless behavior with no indication of resonances with $J^{PC} = 2^{++}$ in the 2.0 - 2.5 GeV mass region where our $\phi\phi$ data lie, but we clearly find the h(2030) in $J^{PC} = 4^{++}$ in striking contrast to its absence in $\phi\phi$. We also do not find the h'(2200) [f_4'(2200)] predicted by Godfrey and Isgur[5] since it would be OZI-suppressed in $\phi\phi$ production.

These very striking phenomena are very naturally explained in the context of QCD by production of 1-3 $I^GJ^{PC} = 0^+2^{++}$ glueballs.[2-3] At least one broad primary $J^{PC} = 2^{++}$ glueball is required to explain the complete breaking of the Zweig suppression and selection of only $J^{PC} = 2^{++}$ resonant states, and the unique observation of these states only in the $\phi\phi$ system. One could in principle then mix with one or two other conventional $q\bar{q}$ states. However the simplest and natural explanation of our data within the

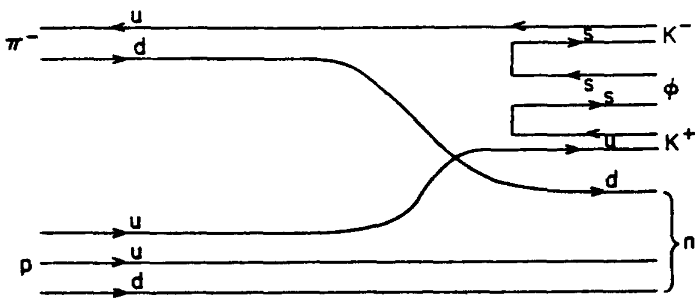

Fig. 1b The Zweig Quark Line Diagram for the reaction $\pi^- p \rightarrow \phi K^+ K^- n$, which is connected and OZI allowed.

context of QCD is that we have found a triplet of $J^{PC} = 2^{++}$ glueballs, which is the expected number of low-lying $J^{PC} = 2^{++}$ glueballs. Although there have been several attempts to explain our data by various other assumptions they have been shown to be incorrect, do not fit the data or both.[3] Another arguement advanced is that perhaps we have seen radially excited mixed states such as the η' which are formed via ordinary u,d quarks and decay via the $s\bar{s}$ quark content.

The 2^{++} nonet is well-known to be ideally mixed. In QCD there are only two basic flavor mixing mechanisms (i.e. $q\bar{q} \rightarrow s\bar{s}$ where q = u,d): 1) Vacuum mixing[18] which mixes the η and η' about as far as possible from ideal mixing. Vacuum mixing is expected to be most important for J = 0. It clearly does not mix the $J^{PC} = 2^{++}$ nonet which is well-established and $\approx$ ideally mixed. Nor does it affect the well-established 1^{--} nonet, and the reasonably established 3^{--} nonet. 2) Glueball mixing.

In a coupled channel partial wave analysis of the 2^{++} world sample of data[4] we have shown that even the $f_r(1810)$ the radially excited f (the singlet of the octet) is composed of u,d quark and anti-quark pairs, and does not have any appreciable $s\bar{s}$ content. Thus it clearly follows that the radial excitation of the $f_2'(1525)$ singlet should be $\approx$ pure $s\bar{s}$. This would correspond to the Godfrey-Isgur[5] $f_2'(2040)$. Hence its production would be Zweig suppressed. Godfrey and Isgur have shown that by assuming ideal mixing[5] for all nonets and their radial excitations* except 0^{-+}, they can explain[5] the experimental data well with their $q\bar{q}$ model. They predict only three 2^{++} states in the mass region of the g_T's. They are 1) the $2^3 P_2$ $f_2'(2040)$ with an $s\bar{s}$ quark pair; 2) the $1^3 F_2$ $f_2(2050)$ with $u\bar{u}$ and $d\bar{d}$ quarks; 3) the $1^3 F_2$ $f_2'(2240)$ with an $s\bar{s}$ quark pair.

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* This is consistent with our $\phi\phi$ observations as we would have expected to see both the h(2030) and the $s\bar{s}$ partner of the h(2030), as well as the $f_2'(2040)$ if the radially excited nonet departed substantially from ideal mixing.

1) The $f_2'(2040)$ and 2) the $f_2'(2240)$ are OZI suppressed in $\phi\phi$ production.

2) The $f_2(2050)$ is OZI suppressed in decay to $\phi\phi$. Therefore we would not see any of these states in $\phi\phi$.

Thus without at least one $J^{PC} = 2^{++}$ glueball destroying the ideal mixing we would not see any expected $q\bar{q}$ state in our $\phi\phi$ experiment. Furthermore there is no explanation why in $\phi\phi$ we see three closely spaced isosinglet $J^{PC} = 2^{++}$ resonances, and nothing else whereas in ϕK^+K^- and $K^0_sK^0_s$ we see virtually all non-resonant background and no evidence of resonances. Thus our data can naturally be explained within the context of QCD by production of 1-3 $J^{PC} = 2^{++}$ glueballs and there is no viable alternate explanation to date[3] which fits its unusual characteristics.[2-3]

THE PARTIAL WAVE ANALYSIS AND K-MATRIX FITS

We used the standard LBL/SLAC isobar model program to analyze our 6658 number of events. Due to the narrowness of the ϕ the analysis becomes independent of the isobar model characteristics. Of course we replaced the spectator particle with the second ϕ which also decays giving us six angles, the Gottfried-Jackson polar and azimuthal K^+K^- decay angles (β,γ) in the $\phi\phi$ system and the polar and azimuthal angles ($\theta_{1,2}$ and $\phi_{1,2}$) in each ϕ rest system. The spin J = 1 of the ϕ makes these six angles and their correlations incredibly powerful wave selectors. We used all waves which satisfy Bose symmetry and have L = 0-4 and J = 0-6 for a total of 114 waves. We simultaneously analyzed the small ϕK^+K^- physical background which occurred at the level of a few percent but used wide cuts (14 MeV) on the ϕ to ensure lack of biases and allow a search for a phase reference wave. This raised the level of this background to $\approx$ 13%. We allowed up to J = 2 (27 waves) in its analysis, so that interference effects could be most accurately taken into account and result in maximum precision. The only other physical effect involved was the four kaon background which occurred at a level ~ 0.1% and thus was of negligible significance.

Figure 2 shows the result of the partial wave analysis of the $\phi\phi$. The three $J^{PC} = 2^{++}$ amplitudes and the phase behavior of the two D-waves relative to the S-wave as a phase reference clearly show resonant phase behavior. The significance of this particular set of waves was 13σ and they gave a good fit to the data. $M^{\eta} = 0^-$ for all three waves which together with the $d\sigma/d|t'| \approx e^{-9.5|t'|}$ for $|t'| < 0.3$ (i.e. $\approx$ 95% of the data) demonstrates that pion exchange is the production mechanism (see Fig. 3). We fit the partial wave analysis results with K-matrix poles which preserve unitarity and correspond on a one-to-one basis with Breit-Wigner resonances. The curves shown in the various figures correspond to our best fit $\approx 2\sigma$. The unitary effects turned out to be small so that even if we had fit with simple complex Breit-Wigners

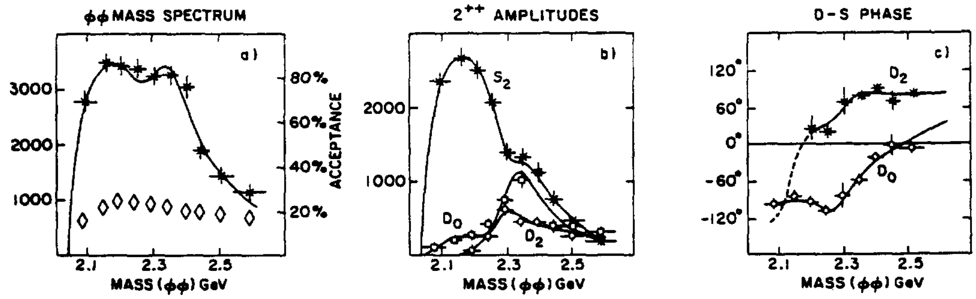

Figure 2: (a) The acceptance corrected $\phi\phi$ mass spectrum, (b) intensity and (c) phase difference for the three $J^{PC} = 2^{++}$ waves. The curves show the fit by three Breit-Wigner resonances (i.e. K-matrix poles).

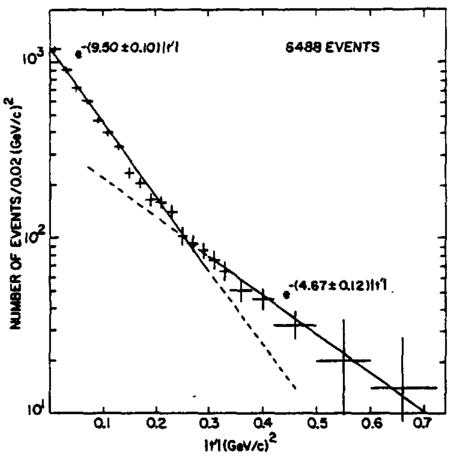

Fig. 3: log(const. × $d\sigma/dt'$) plotted versus $|t'|$.

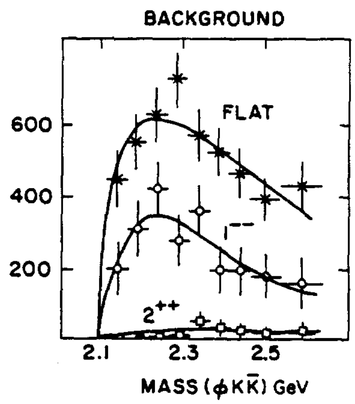

Fig. 4: Intensity of the partial waves in the background reaction $\pi^- p \rightarrow \phi K^+ K^- n$.

we would have obtained consistent values. A partial wave analysis of the physical background reaction $\phi K^+ K^- n$ (Fig. 4) shows ≈ 67% flat (in all angular variables) background, only ≈ 3%, $J^{PC} = 2^{++}$ in the $\phi\phi$ and ≈ 30% $J^{PC} = 1^{--}$ (the expected result for all particles in a relative S-wave produced by pion exchange).

In order to calculate absolute phase motion we used the 1^{--} $\phi K^+ K^-$ wave (which is coherent with the $\phi\phi$ waves as shown by interference) as a phase reference (Fig. 5b). As shown in Fig. 5 we then converted our $\phi\phi$ phases to absolute phase for the two extreme cases. a) If one assumes $\phi K^+ K^-$ is caused by a peripheral reggeized Deck type mechanism one expects to obtain the minimum phase taversal of the 1^{--} wave over the mass region of the $\phi\phi$ data. b) Assuming that the 1^{--} wave corresponds to a resonance (K-matrix pole) gives the maximum phase traversal and the resultant absolute phase, gave the Argand diagrams shown in Fig. 5a and 5c. Both extreme cases gave similar classic Breit-Wigner three

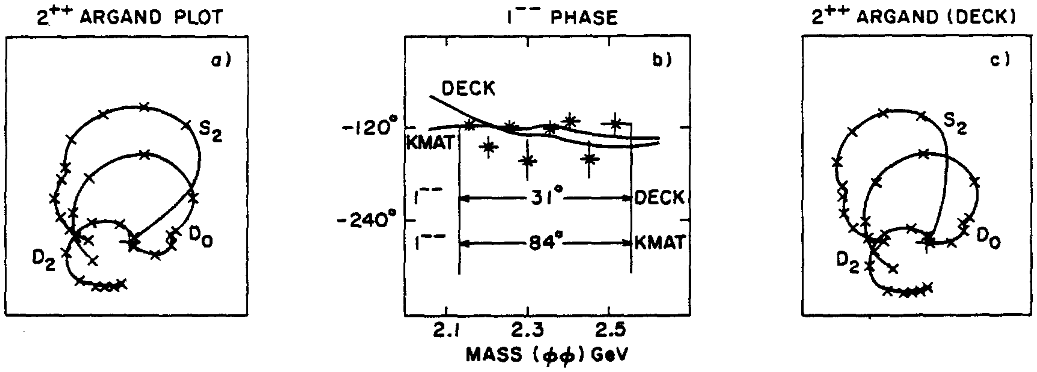

Figure 5: (a) Argand plots for the three 2^{++} waves with the absolute phase based on the 1^{--} $\phi K\bar{K}$ wave being a Breit-Wigner resonance (K-matrix), while (c) is based on the 1^{--} $\phi K\bar{K}$ resulting from a deck mechanism. (b) shows the 1^{--} phase (relative to the S-wave in $\phi\phi$). The curves come from the two models stated for the 1^{--} absolute phase.

resonance behavior. Thus the actual case which lies in-between these extremes obviously has classic Breit-Wigner resonance behavior for all three resonances, as demonstrated by our good 3 K-matrix pole fit.

The parameters of the Breit-Wigner resonances etc. are given in Table I.

TABLE I

Parameters of the Breit Wigner Resonances (corresponding to the K-matrix poles) and percentage of the resonances going into 2^{++} S_2, D_2, and D_0 channels. The errors come from a complete study of the χ^2 surface.

State	% of $\phi\phi$ Data	Mass (GeV)	Width (GeV)	S_2(%)	D_2(%)	D_0(%)
g_T	45	$2.011^{+0.062}_{-0.076}$	$0.202^{+0.067}_{-0.062}$	98^{+1}_{-3}	0^{+1}	2^{+2}_{-1}
$g_{T'}$	20	2.297 ± 0.028	0.149 ± 0.041	6^{+15}_{-05}	25^{+18}_{-14}	69^{+16}_{-27}
$g_{T''}$	35	2.339 ± 0.055	$0.319^{+0.081}_{-0.069}$	37 ± 19	4^{+12}_{-4}	59^{+21}_{-19}

COMPARISON WITH SLAC MK III AND RELATED RESULTS

Another filter studied for enrichment of glueballs compared to conventional $q\bar{q}$ states is the radiative decay of the $J/\psi \to \gamma gg$ or hopefully preferentially $J/\psi \to \gamma G$ where G is a glueball. The question hs been raised at this conference and elsewhere[17] as to why our $\phi\phi$ states have not been seen in this channel. In order to answer this we must consider the characteristics of this channel and compare to our channel. In the radiative decay of the J/ψ conventional $q\bar{q}$ states such as η, η' in $J^{PC} = 0^{-+}$ and f, f' in $J^{PC} = 2^{++}$ are seen with relatively sizeable cross sections compared to the glueball candidates iota and θ respectively. Furthermore there are relatively large cross sections of the general continium (at least unresolved into resonances) type with both quantum numbers. Therefore the J/ψ radiative decay channel clearly cannot be a tight glueball filter or these conventional objects would not appear in it. This is in contrast to the $\pi^- p \to \phi\phi n$ where no conventional objects such as the flat featureless background that appears in $\pi^- p \to K_S^0 K_S^0 n$ does not appear in $\phi\phi$. The h(2030) with $J^{PC} = 4^{++}$ does not show even a trace in $\pi^- p \to \phi\phi n$ even though we can very easily detect even small amounts of it with the enormous analysis power of the $\phi\phi$ system. In fact nothing conventional or anything else is found except the three $J^{PC} = 2^{++}$ g_T, $g_{T'}$ and $g_{T''}$ resonances. Thus there are huge factors in the filter action for glueballs in favor of the $\pi^- p \to \phi\phi n$ channel. Secondly the width of the $J/\psi \to ggg$ agrees with perturbative calculations. The branching ratio $J/\psi \to \gamma gg$ also agrees with perturbative calculations. Therefore if J/ψ radiative decay were strongly coupled to glueballs one might expect that the process $J/\psi \to \gamma G$ would enhance the radiative decay branching ratio and in the process increase the width of the J/ψ. As far as we know no theorist has properly addressed this question although we have raised it before.

The MK III collaboration[7] reported that in J/ψ radiative decay they observe several hundred $\phi\phi$ which they conclude have $J^{PC} = 0^{-+}$ and see very little $J^{PC} = 2^{++}$ $\phi\phi$ in the remainder. In J/ψ radiative decay one would expect the 0^{-+} channel to be strongly enhanced, since the process $J/\psi \to \gamma\eta_c(\text{virtual}) \to \gamma$ hadrons (with $J^{PC} = 0^{-+}$) would be expected to be enhanced because it proceeds via spin flip of the $c\bar{c}$ pair and is also enhanced at high masses (2.0 - 2.5 GeV) by the influence of the η_c pole at 3.1 GeV. Therefore with limited statistics (a few hundred) a 0^{-+} $\phi\phi$ continuum (or other resonances) could well be enhanced and accompanied by relatively few $\phi\phi$ in a 2^{++} state. The expected relative strength of the 0^{-+} channel in J/ψ radiative decay is consistent with MK III data. It should be noted that in $\pi^- p \to \phi\phi n$, the production process for glueballs would be as previously noted $\gtrsim 95\%$ $\pi^-\pi^+ \to G$ and thus only 0^{++}, 4^{++}, 6^{++} .... etc. would be seen. Thus we would not see the 0^{-+} channel in our experiments. Secondly as previously discussed since conventional $q\bar{q}$ objects or continuum are obviously from our results filtered out, we would not expect to see anything that does not contain resonating gluons. Therefore we do not feel there is any basis for believing there is an inconsistency between the two experiments. One should also note that although such estimates are difficult to make, Sinha, Okubo and Tuan[8] estimated

[B $J/\psi \to g_{T+\gamma}$] $\times$ B ($g_T \to \phi\phi \approx 0.7 \times 10^{-5}$) whereas MK III limits are $< 8.6 \times 10^{-5}$. In any event as I discussed previously MK III clearly does not have either the statistics or effective glueball filter action needed to see the BNL/CCNY $\phi\phi$ states.

However in comparing our investigation on another reaction $\pi^- p \to K_S^0 K_S^0 n$ and our coupled channel K-matrix unitary analysis using the world data[4] including MK III, we could not reconcile our analysis of the LASS experiment on $\pi^- p \to K_S^0 K_S^0 \Lambda$,[9] and the MK III data on the 2^{++} channel which contains the f and f' and θ. We found in that analysis that LASS should have seen the θ at a level ~ 0.4 the f' peak, Fig. 6a-b. However, LASS does not see the θ down to a level of a few percent. If we leave the SLAC MK III data out we could fit all hadronic experiments easily. If we leave the LASS data out we can also fit the remaining data but we had not succeeded in fitting both.

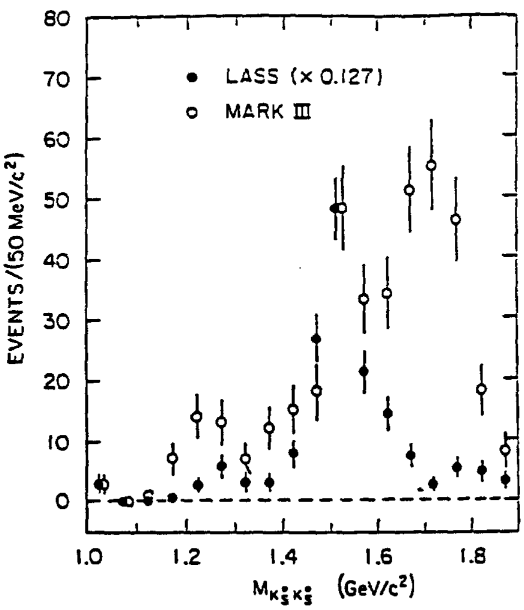

Fig. 6a The comparison of the $K_S^0 K_S^0$ mass distribution from LASS and MK II with that from radiative J/ψ decay from threshold up to 1.9 GeV/c^2.

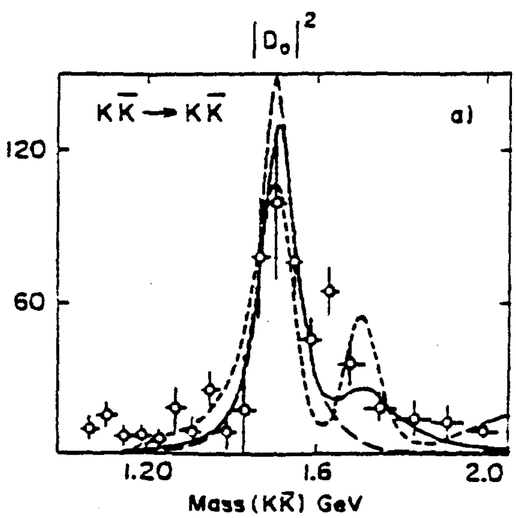

Fig. 6b The modulus square of the D_0 amplitude in events as a function of mass in GeV compared to coupled channel prediction.[4]

Our difficulty of fitting the LASS experiment and the J/ψ radiative decay simultaneously in our coupled channel analysis,[4] led Lindenbaum and Longacre to request from Walter Toki of Mark III the latest information on the status of the θ quantum numbers. The Bolton Thesis[11] which he sent us made it clear that one could not distinguish between 0^{++} and 2^{++} or a mixture for the θ quantum numbers.[15] It also became clear to us that the previous[12] assignment of $J^{PC} = 2^{++}$ for the θ was based on the naive assumption that one could test for one spin at a time over the whole region with very limited statistics in the reaction $J/\psi \to \gamma K^+K^-$. This naive and very unreliable approach was used instead of doing what is required to assign the quantum numbers, namely perform a partial wave analysis considering all the likely J^{PC} simultaneously. That one should not place any serious credence in this prior analysis was made clear by the Bolton Thesis[11] which showed that this naive method preferred $J^P = 0^+$ instead of 2^+ for the 85 K^+K^- data even when the 82-83 data was included. When the original 82-83 data was used it preferred 2^+. Bolton then performed a minimal partial wave analysis allowing J = 0 and J = 2 with interference occurring simultaneously. The result is shown in Fig. 7. In the f' region spin 2 is clearly selected whereas in the θ region spin 0 is selected. Thus contradicting the earlier naive published analysis.[12] However since the statistics are limited and there may well be other amplitudes present we conclude that there is not enough statistics with a sophisticated enough analysis to assign the θ quantum numbers. The most one can say is that 0^{++} and 2^{++} or a mixture is not distinguishable.

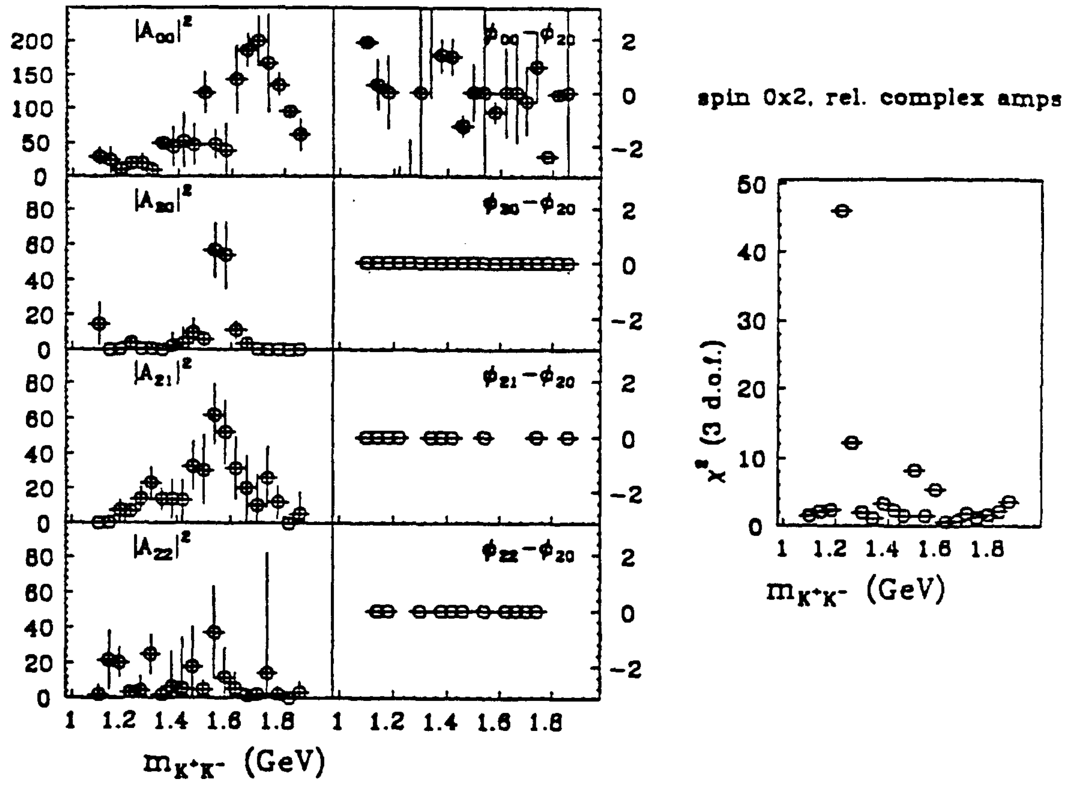

Figure 7 Amplitude fits for γK^+K^- (spin 0 × 2 parameters.

In the $J/\psi \to \gamma K^0_S K^0_S$ reaction the $K^0_S K^0_S$ system in the θ region under the previous naive hypothesis of one spin at a time favors $J^P = 2^+$. However if spin 2 and spin 0 interfering are allowed (Fig. 8) and Table II (Table V from Ref. 11), which is a minimal (statistics lumped in one bin with $J = 0^{++}, 2^{++}$) acceptable analysis, and the only part of Table II that should be considered. It gives an ≈ 4σ selection of $|A_{00}|^2$ (i.e. the J = 0 amplitude squared), whereas all $J = 2$ amplitudes have less than 2σ significance. MK III concludes this $J/\psi \rightarrow \gamma K_S^0 K_S^0$ reaction is the "clean" one and more suitable to assign quantum numbers. However the statistics and analysis are both clearly limited. Thus it is clear that spin 0 is either favored or better to say there is insufficient statistics to decide between 0^{++} and 2^{++} or a mixture of both. We found the content of Dave Hitlin's[6] and Walter Toki's[16] talks at this conference consistent with this conclusion. Thus the above is the most one can say about the quantum numbers of the θ.

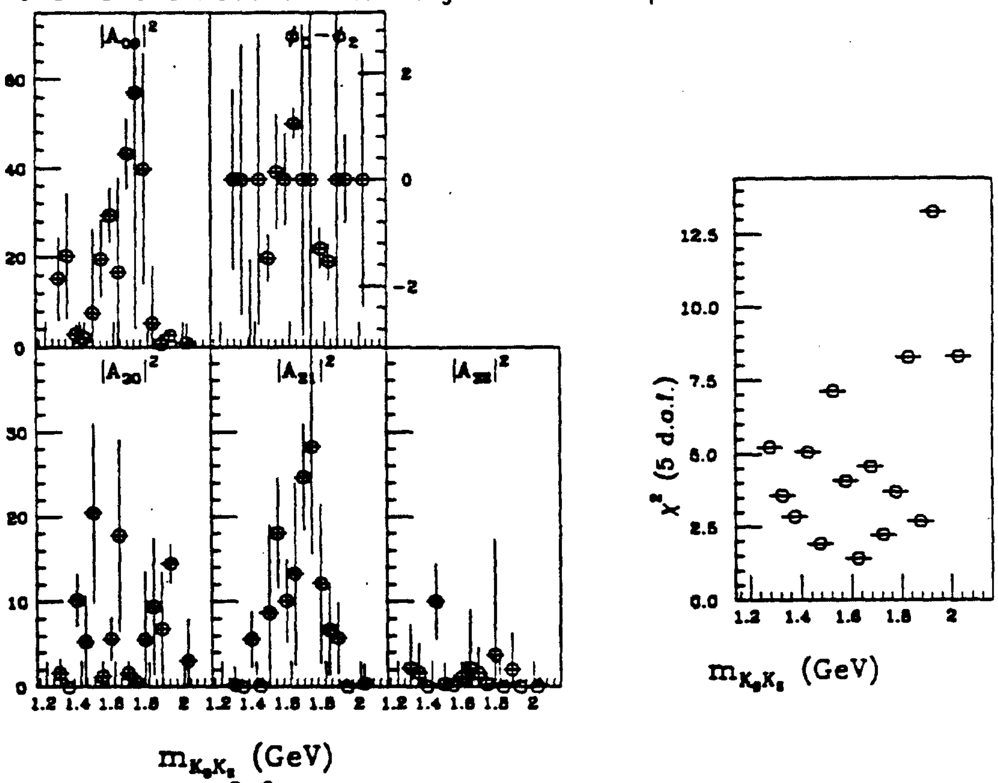

Figure 8 $K_S^0 K_S^0$ amplitude analysis results (spin 0 × spin 2).

In regard to reconciling the MK III and LASS experiments, Liu[19] has followed his theoretical prejudice that the tensor glueball is a large object while mesons are effectively point-like in comparison. He then inserts a form factor for the θ in the s-channel of the form e^{-Q^2/Λ^2} with $\Lambda^2 = 1$ GeV^2/c^2 chosen to strongly suppress the $\pi\pi$ decay mode and also raises the $\eta\eta$ decay mode of the θ compared to the $K\bar{K}$ mode. He achieves reasonable agreement with the θ decay by this ad hoc means.

Since all mesons are thought to be extended objects of $q\bar{q}$ pairs connected by glue strings there is no justification of this ad hoc distinction between meson sizes and glueball sizes. In particular his $\Lambda^2 \approx 1$ GeV^2/c^2 corresponds to a size for the glueball of ~ 1/5 fermi and thus this approach would require u, d, s $q\bar{q}$ mesons to be effectively point-like compared to ~ 1/5 fermi, contradicting what one would expect from any potential or other conventional model.

Table II: Results of $K_S^0 K_S^0$ spin fits: amplitudes

quantity	1.10-1.40 GeV	1.45-1.60 GeV	1.65-1.85 GeV
$\chi^2(J=0)$	9.2/9	17.7/9	16.7/9
$\chi^2(J=2)$	8.3/7	4.7/7	13.1/5
$x(\phi_x \equiv 0)$	1.09 ± 0.31	1.12 ± 0.22	-1.35 ± 0.20
$y(\phi_y \equiv 0)$	-0.73 ± 0.32	-0.06 ± 0.26	-0.61 ± 0.22
$\chi^2(J=2)$	7.8/5	4.4/5	7.0/5
$\mid x \mid$	1.07 ± 0.31	1.11 ± 0.21	1.22 ± 0.24
$\mid y \mid$	0.73 ± 0.35	0.06 ± 0.29	0.68 ± 0.30
ϕ_x	1.1 ± 0.3	-1.0 ± 0.9	1.6 ± 1.1
ϕ_y	-2.2 ± 1.2	-3.1 ± 6.4	-1.9 ± 0.6
$\chi^2(J=0 \times 2)$	3.1/5	0.6/5	1.9/5
$\mid A_{00} \mid^2$	39 ± 17	43 ± 27	96 ± 25
$\mid A_{20} \mid^2$	2 ± 3	16 ± 11	6 ± 10
$\mid A_{21} \mid^2$	0 ± 2	18 ± 13	25 ± 15
$\mid A_{22} \mid^2$	9 ± 13	29 ± 9	2 ± 6
$\phi_{00} - \phi_{20}$	0.6 ± 0.6	1.0 ± 0.3	0.9 ± 0.5

Furthermore many successful calculations have been performed on meson decay branching ratios without use of this new ad hoc approach. The study of mesons and baryons and their decays have shown that Blatt and Weisskopf barrier factors due to finite size are very important for $q\bar{q}$ and qqq states [F. Von Hippel and C. Quigg, Phys. Rev. D5, 624 (1972)]. Thus using only $q^{2\ell+1}$ without them as in Ref. 19 is not correct at these high cm energies.

It should be noted that these conventionally used finite size barrier factors saturate at high q^2 and have a totally different behavior than Liu's.

He then goes on to analytically continue this procedure into the t-channel for off-shell $K\bar{K}$ interactions and succeeds in making the expected θ peak dissappear in the LASS experiment. There is no demonstration that such a new procedure is justified. In fact there have been many successful consistent analyses using the well-known one-particle exchange model (OPE) without Liu's form factors, and the OPE conventional model has fit the data well.

OPE has a factorization of the t-channel dependence from s-channel behavior. The t behavior depends on the lower vertex production (flip or nonflip) and the particle exchange quantum numbers and slope. Once the amplitudes for the t-channel are separated into their independent modes, a partial wave expansion is performed in the final meson system as a function of s.

His ideas of introducing his new type of size form factors in the t-channel would drastically change some of these results. He would at least have to look at the whole problem of both s-channel decays of various mesons and the t-channel production of various mesons to see if his ad hoc assumption explains the data.

As we have already discussed[15] the Bolton Thesis[11] demonstrates the J^{PC} of the θ could be 0^{++} at least as easily as 2^{++}. The disappearance of the θ peak in the LASS experiment is a direct result of the conventional and successful one meson exchange model if the θ $J^{PC} = 0^{++}$ which is discussed in this paper and also Refs. 10 and 15. It is clearly premature to take the MK III assigned $J^{PC} = 2^{++}$ for the θ as correct.

While we are on the subject of the θ, some other remarks about the θ situation are appropriate. It has been common,[6] but in our opinion, unjustified practice to associate experimentally observed bumps in various reactions with the SLAC $\theta(1720)$ for which the assignment $J^{PC} = 2^{++}$ is claimed, but as discussed in this paper not established.

For example in the WA76 experiment at CERN[20] observation of a structure similar in shape to the θ in the reactions $pp \to p_f(K^+K^-)p_s$, $pp \to p_f(K_S^0K_S^0)p_s$ was associated with the θ even though the authors were not able to determine its quantum numbers and in particular distinguish $J^{PC} = 0^{++}$ from $J^{PC} = 2^{++}$ or other (even) ++ assignments.

Thus it could well have been the $S^{*\prime}$ with $J^{PC} = 0^{++}$ or some other object(s). Perhaps not even a resonance, since no partial wave analysis was performed.

MK III[6] has on various occasions considered a peak in the region of the $J^{PC} = 2^{++}$ $\theta(1720)$ and argued about its lack of strong preference for a particular quark flavor from observations in J/ψ decay. Since they have not established the quantum numbers of the θ observed in radiative decay or that the alluded to observed states are resonances with definite quantum numbers, these conclusions are not justified. For example if $J^{PC} = 0^{++}$ there is the possibility of considerable flavor mixing.

If there is more than one $q\bar{q}$ state involved each could have a different flavor structure and one could not be sure what one is observing.

In other words without a proper sophisticated enough, and significant enough partial wave analysis these claims are unjustified.

COUPLED CHANNEL ANALYSIS OF 0^{++} AND 2^{++}

Thus for the purposes of our coupled channel analysis which originally[4] assumed J^{PC} of the θ was 2^{++}, we now will instead follow two scenarios: A) the J^{PC} of the $\theta = 2^{++}$; B) the J^{PC} of $\theta = 0^{++}$. As previously stated a mixture of both is also possible.

If the θ should have $J^{PC} = 0^{++}$ an interesting coincidence then occurs. Then the $S^{*\prime}$ a state discovered[13] before the θ,[12] with about the same mass ($M \approx 1712$) and width as the θ ($\Gamma \approx 185$) but with $J^{PC} = 0^{++}$ could be the same as the θ, and we will make this assumption in scenario B), we will follow, the usual principle of maximal simplicity (i.e. minimum number of poles) in fitting the data. Note: scenario A is already contradicted by the LASS experiment.

In the case of scenario B [$J^{PC}(\theta) = 0^{++}$], the first thing that happens is the prediction of our coupled channel analysis[4] that LASS should have seen the θ changes so that the lack of the θ in the LASS data is predicted, Fig. 9a.[10,15]

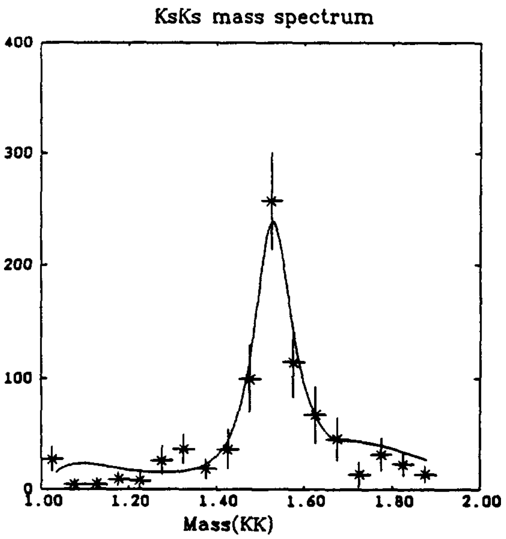

Figure 9a

A comparison of the LASS data with our fit (scenario B) where θ and $S^{*\prime}$ are the same with $J^{PC} = 2^{++}$.

Furthermore the status of the G(1590) comes into question since those authors[14] used an anamolously low mass $\varepsilon(\sim 1230 \pm 30)$ in their fit which gave the G(1590) whereas an ε with mass in the range $\varepsilon \sim 1450 \pm 50$ MeV is representative of most other works. This subject was previously discussed in Ref. 15.

I will now report on a minimal coupled channel 0^{++} and 2^{++} analysis which has yielded significant preliminary results but which is still in progress.[10] The S-wave was fitted from 600 MeV to 1900 MeV.

The D-wave was fitted from 1,000 MeV to 1600 MeV† using the relevant data on final states which involve two pseudoscalars.

The data we used was from the reactions $\pi\pi \to \pi\pi$, $\pi\pi \to K\bar{K}$, $\pi\pi \to \eta\eta$, $\pi\pi \to \eta\eta'$, $K\bar{K} \to K\bar{K}$, $J/\psi \to \gamma\pi\pi$, $J/\psi \to \gamma K\bar{K}$, $J/\psi \to \gamma\eta\eta$, and $J/\psi \to \gamma\eta\eta'$. We found we needed only 2 poles to fit the D-wave in the f to θ region. f(1272) with Γ = 187 Mev; f'(1528) with Γ = 135 Mev.

To fit the S-wave we needed four poles in our simplest and thus favored scenario B: S^*(1060 with Γ = 158; ε(1478) with Γ = 246; $S^{*\prime}$(1712) with Γ = 185; g_S(1266)[13] with Γ = 315 Mev, plus a background pole M = 2116 Mev, Γ = 11,610 Mev in which the following decay modes were included: In the D-wave, f $\to \pi\pi$, $K\bar{K}$, $\eta\eta$; f' $\to \pi\pi$, $K\bar{K}$, $\eta\eta$; $S^* \to \pi\pi$, $K\bar{K}$; $\varepsilon \to \pi\pi$, $K\bar{K}$, $\eta\eta$, $\eta\eta'$; $S^{*\prime} \to \pi\pi$, $K\bar{K}$, $\eta\eta$, $\eta\eta'$; $g_S \to \pi\pi$, $K\bar{K}$, $\eta\eta$. Some results of the reasonable fit we obtained are shown in Fig. 9.

In scenario C the D-wave remained the same but we replaced the g_S of scenario B with the G(1590) and included the following decay modes for the poles: $S^* \to \pi\pi$, $K\bar{K}$, $\eta\eta$; $\varepsilon \to \pi\pi$, $K\bar{K}$; $S^{*\prime} \to \pi\pi$, $K\bar{K}$; G $\to \pi\pi$, $\eta\eta$, $\eta\eta'$. Some results of scenario C are shown in Fig. 10 and it is evident that in $|S|^2$ the fits to $\pi\pi \to \eta\eta$ and $\psi \to \gamma\eta\eta$ are unacceptable. Therefore this scenario is rejected.

Although we have identified the important minimal poles needed to fit the data in 0^{++} and 2^{++} coupled channel analyses we are still working on making the coupled channel analysis unitary in a K-matrix formalism and completing it.

However from our prior experience we expect this will not change our conclusions significantly. Namely that in the simplest successful scenario using the minimum number of poles the θ is the same as the $S^{*\prime}$ with $J^{PC} = 0^{++}$ and the g_S, S^*, ε, $S^{*\prime}$ poles fit to the data is acceptable while replacing the g_S (or any other pole) with the G does not lead to an acceptable fit.

What about Exotic Glueballs (Oddballs)? One calls a particle exotic if its J^{PC} cannot be made from a $q\bar{q}$ pair. This obviously does not apply to glueballs which one could expect could easily have exotic quantum numbers. However our $\phi\phi$ production process obviously involves π-exchange (i.e. $\pi^+\pi^-$ annihilation into gluons) therefore we can only have $J^{PC} = 0^{++}, 2^{++}, 4^{++}$ ... and thus cannot make exotic glueballs. However as you can see from Fig. 3 for $|t'| > 0.3$ there is a break in slope toward smaller slopes implying that A-exchange etc. which can make exotic glueballs can occur. At present only about 5% of our data is in this region

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† Since the θ is now in the s-wave its peak disappears from the D-wave.

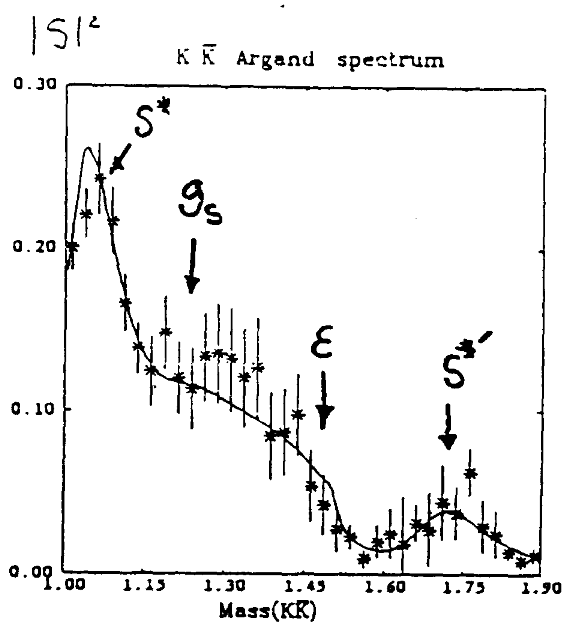
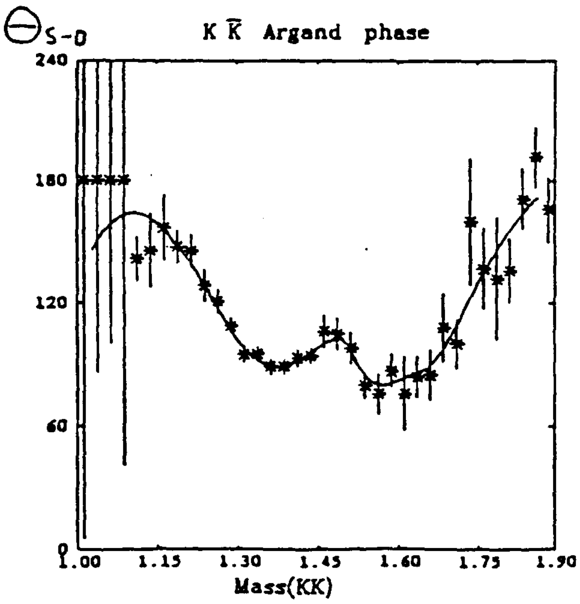


Figure 9b

Our fit (scenario B) compared to the data for $\pi\pi \rightarrow K\bar{K}$.



which are clearly too few events to allow a serious analysis. We plan in our next runs to enhance observation of A-exchange by a factor ~ 8 by going to lower energies and increasing our apparatus acceptance. This fit is also consistent with the low statistics $J/\psi \rightarrow \gamma\eta\eta'$. This will also improve our statistics per unit time in π-exchange. Our goal will be to search for possible oddballs (exotic J^{PC}). The question of the mass of such glueballs is of course quite uncertain. However an experimental search in the mass region we have available is clearly the next step in this glueball program.

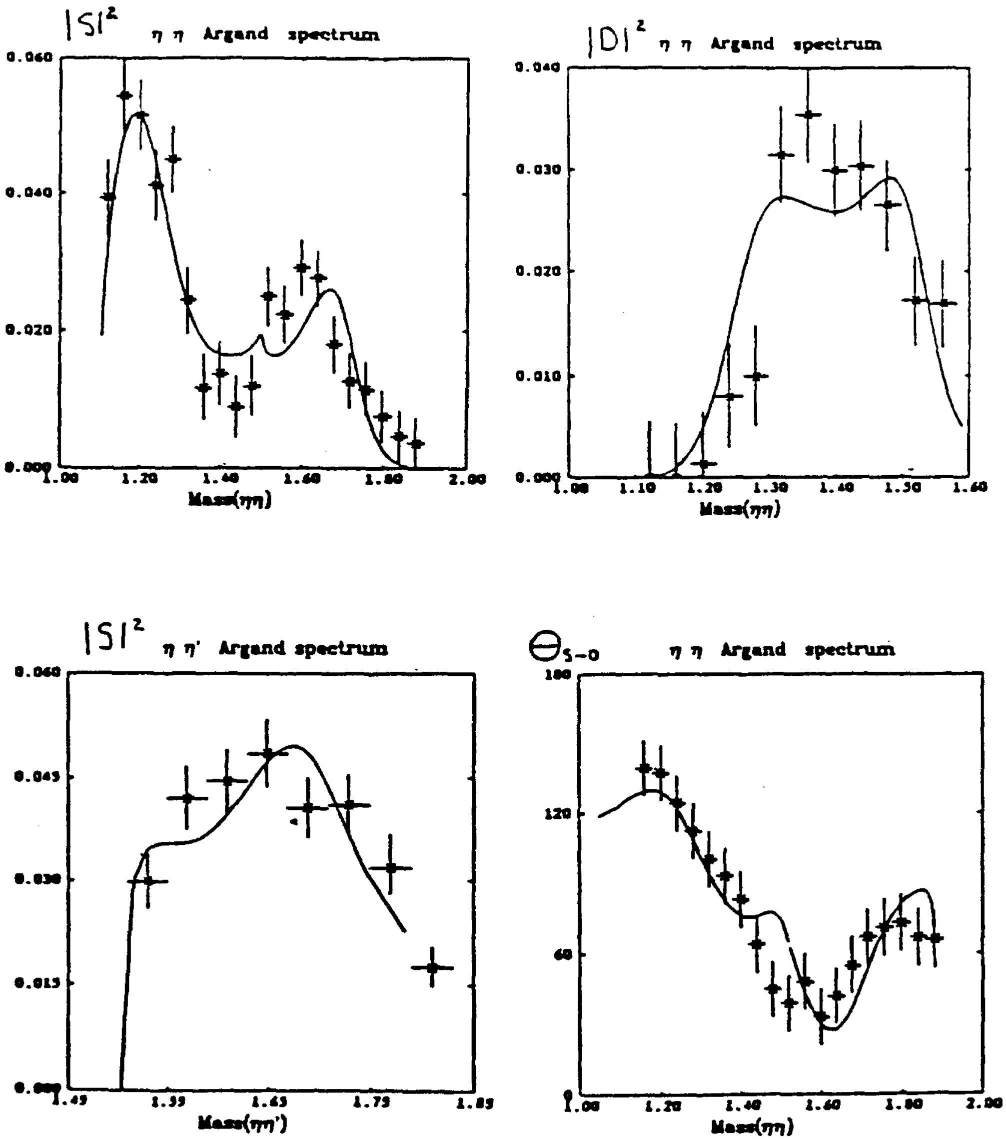


Figure 9c: $\pi\pi \rightarrow \eta\eta$, $\eta\eta'$

SUMMARY

We have gathered and partial-wave analyzed 6658 events of $\pi^- p \rightarrow \phi\phi n$, and for maximum precision simultaneously analyzed the small physical background reaction $\pi^- p \rightarrow \phi K^+ K^- n$ accompanying the $\phi\phi$. We find the $\phi\phi$ which is OZI-forbidden towers above the ϕK^+K^- which is OZI-allowed by a factor ~ 50 when corrected for resolution. The $\phi\phi$ events are composed entirely within errors of three $I^G J^{PC} = 0^+ 2^{++}$ resonances the $g_T(2010)$, $g_T{}'(2300)$ and $g_T{}''(2340)$ whereas in contrast the ϕK^+K^- is mostly structureless background, shows no evidence for resonances and has only 3% $J^{PC} = 2^{++}$ compared to the $\phi\phi$ which has (within errors) 100% resonant 2^{++}. We were able to use the coherent 1^{--} wave of the ϕK^+K^- to calculate

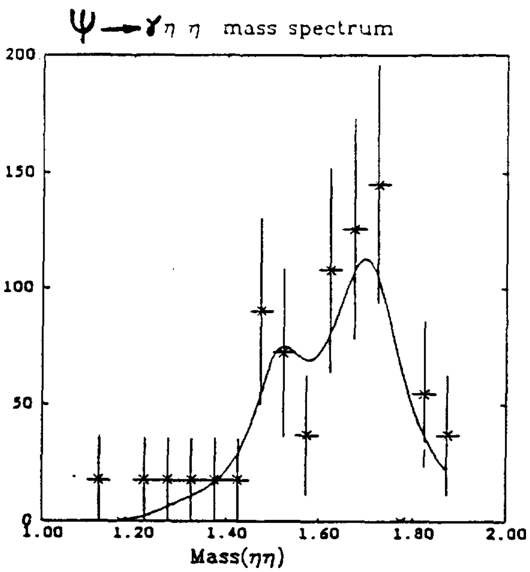


Figure 9d
$J/\psi \rightarrow \psi\eta\eta$

absolute phase ranges for all three $\phi\phi$ resonances and show that they exhibit classic Breit-Wigner resonance Argand plot behavior. They have been shown to be produced by the mechanism of pion exchange. In contrast all other $J^{PC} = 2^{++}$ channels in the 2.0 - 2.5 GeV region (the mass range of the g_T's) do not show any of these resonances. However the h(2030) is seen[4] and its $s\bar{s}$ partner the predicted f_4'(2200) is probably seen in other channels.

Thus we have found a set of very striking phenomena which have not been explainable by conventional means. The striking characteristics of our data can be naturally explained by assuming that 1-3 primary glueballs with $J^{PC} = 2^{++}$ produce these states. At least one broad primary $J^{PC} = 2^{++}$ glueball is necessary to explain the selective breakdown of the OZI suppression and the strong filtering which led to the absence of other states such as the h(2030) and background found in other experiments. Other attempts to explain our data have been shown to be incorrect, do not fit the data or both.[3]

A comparison with the SLAC MK III J/ψ radiative decay was made and it was concluded that due to the fact that they must have a much weaker glueball filter as evidenced by their seeing $q\bar{q}$ states such as η, η', f, f', etc. and background, and have poor statistics, there is no inconsistency in their not seeing our $\phi\phi$ states. Furthermore their radiative decay process should favor 0^{-+} especially at the high masses. We cannot observe 0^{-+} due to the π-exchange production mechanism. We also found from a unitary coupled channel analysis of the world's data that we could not understand the absence of the θ in the LASS experiment $K^-p \rightarrow K_S^0 K_S^0 \Lambda$. An attempt by Liu[19] to solve this problem was discussed earlier in the paper and we do not consider it a satisfactory resolution of the problem for the reasons previously stated.

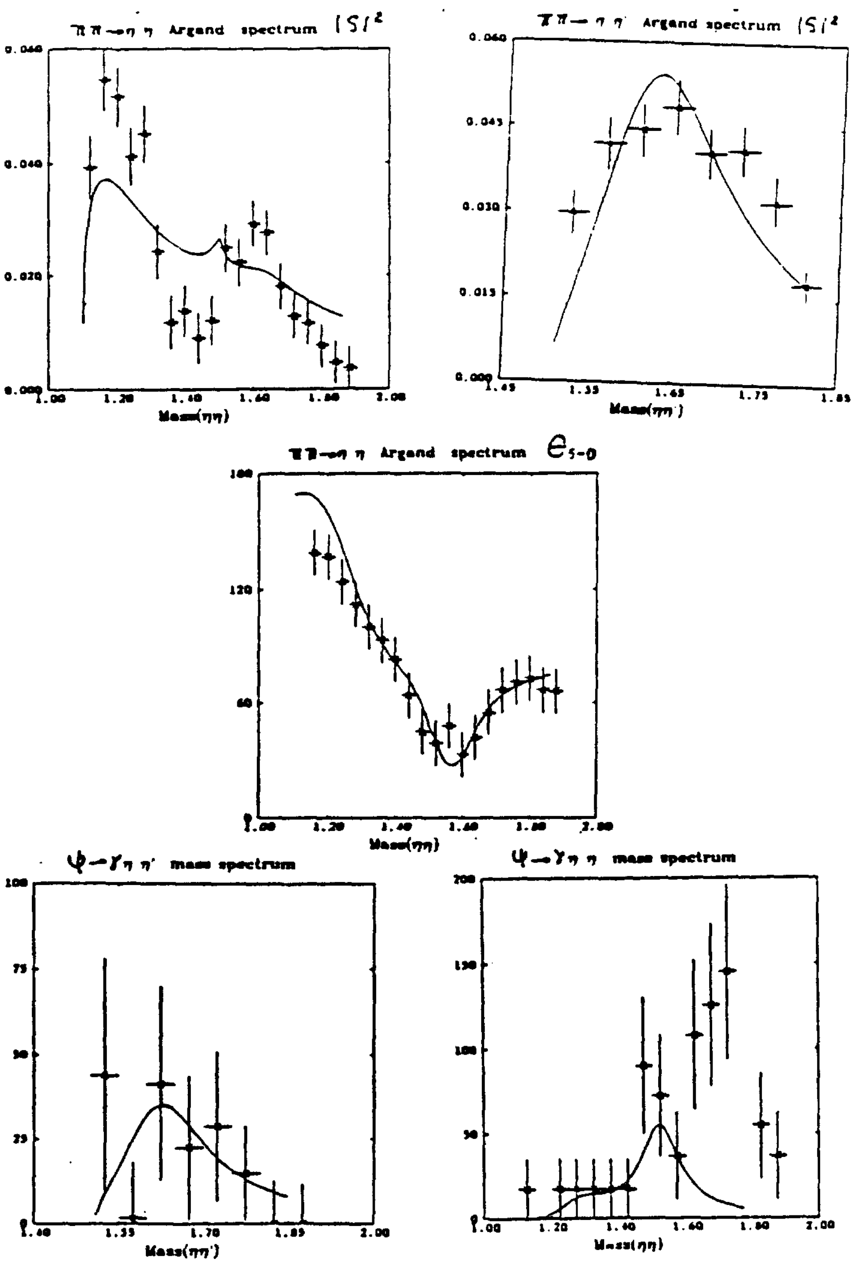


Fig. 10 Scenario C, S-wave titled with G(1590) instead of $g_S(1266)$. Here we clearly do not fit $\pi\pi \rightarrow \eta\eta$ (upper left) or the $J/\psi \rightarrow \gamma\eta\eta$ (lower right). Thus Scenario C is unacceptable.

From new evidence on the J^{PC} of the θ[11] and the lack of convincing evidence in the previous publication[12] we have demonstrated that the J^{PC} of the θ cannot be differentiated from $J^{PC} = 0^{++}$ or 2^{++} or a mixture.

If the θ has $J^{PC} = 0^{++}$, since the mass and width are the same (within errors) as the $S^{*\prime}$, the simplest assumption to make is that the two are the same particle. With the f, f' (D-wave), and S^*, g_S, ϵ, and $S^{*'}$, plus a broad background pole in the S-wave, the LASS experiment and the other available data are reasonably fit with a minimum number of poles. This cannot be done if the G replaces the g_S thus raising questions on the status of the G as discussed in the paper.

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