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INVESTIGATION OF RESONANCE STATES IN THE GLUEBALL-ENHANCED CHANNEL $\pi^- p \rightarrow \phi\phi n$ †

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S.J. Lindenbaum
Brookhaven National Laboratory and City College of New York

K.J. Foley, S.E. Eiseman, A. Etkin, R.W. Hackenburg,
R.S. Longacre, W.A. Love, T.W. Morris, E.D. Platner,
A.C. Saulys
Brookhaven National Laboratory, Upton, New York 11973

C. Chan, M.A. Kramer
City College of New York, New York, New York 10031

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ABSTRACT

In this paper we discuss the striking evidence 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. 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.

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Since 1978[1-2] we have used the OZI-forbidden reaction $\pi^- p \to \phi\phi n$ hoping the pure glue intermediate state would resonate for glueballs (see Fig. 1) 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.

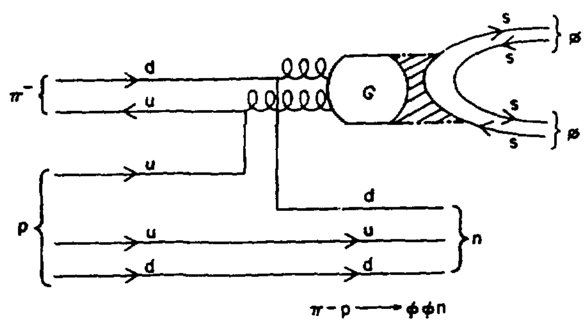

Figure 1: $\pi^- p \to Gn \to \phi\phi n$ Quark Line Diagram

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 $I^G J^{PC} = 0^+2^{++}$ 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^- OZI-allowed physical reaction which has mostly a featureless background and no evidence for any particular resonances. They also tower over the $K^+K^-K^+K^-$ reaction 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) ($I^G J^{PC} = 0^+4^{++}$) which should be strongly produced in π-exchange thus showing how good the filtering action of this channel is against $q\bar{q}$ states. This is consistent with what one would expect from the reaction shown in Fig. 1. In contrast in $\pi^- p \to \phi K^+K^- n$ where the K^+K^- pair is just above the ϕ in mass so that the kinematics etc. are very similar we find ≈ 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 $\pi^- p \to K^0_S K^0_S n$ in the region of the g_T resonances[4] we find a structureless behavior with no indication of resonances in the $J^{PC} = 2^{++}$ 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 $\phi\phi$.

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 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. $q\bar{q} \to s\bar{s}$ where q = u,d): 1) Vacuum mixing 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 ≈ 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 ud quark and anti-quark pairs, and does not have any appreciable $s\bar{s}$ content. Thus it clearly follows that the radially excited singlet should be ≈ pure $s\bar{s}$. Hence its production would be Zweig suppressed. 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 $K_S^0K_S^0$ 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 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 each of 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

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* Comment by F. Close during discussion.

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. This raised the level of this background to ≈ 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

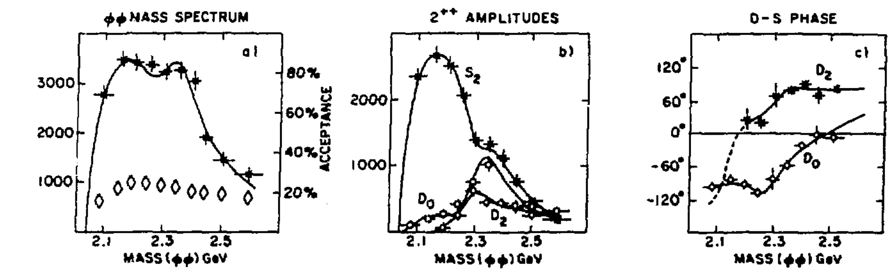

Figure 2: (a) The acceptance corrected $\phi\phi$ mass spectrum, (b) intensity and (c) phase difference for the three $J^{PC} = 2^{++}$ waves. The curves show the fit by three Breit-Wigner resonances (i.e. K-matrix poles).

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 dσ/dt' ≈ 9.5 for $|t'| < 0.3$ (i.e. ≈ 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 ≈ 2σ. The unitary effects turned out to be small so that even if we had fit with simple complex Breit-Wigners we would have obtained consistent values. A partial wave analysis of the physical background reaction ϕK^+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 relative S-wave produced by pion exchange).

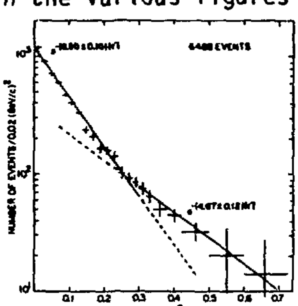

Fig. 3: log(const. × dσ/dt') plotted versus $|t'|$.

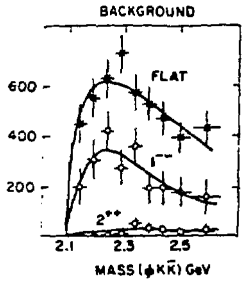

Fig. 4: Intensity of the partial waves in the background reaction $\pi^- p \to \phi K^+ K^- n$.

In order to calculate absolute phase motion we used the 1^{--} ϕK^+K^- wave (which is coherent with the $\phi\phi$ waves as shown by interference) as a phase reference. As shown in Fig. 5 we then converted our $\phi\phi$ phases to absolute phase for the two extreme cases. a) If one assumes ϕK^+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 resonance behavior. Thus the actual case which lies in-between these extremes obviously has classic Breit-Wigner resonance behavior for all three resonances.

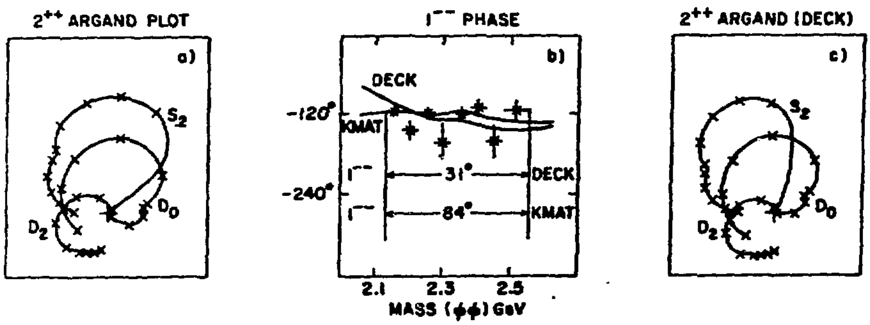

Figure 5: (a) Argand plots for the three 2^{++} waves with the absolute phase based on the 1^{--} $\phi K\bar{K}$ wave being a Breit-Wigner resonance (K-matrix), while (c) is based on the 1^{--} $\phi K\bar{K}$ resulting from a deck mechanism. (b) shows the 1^{--} phase (relative to the S-wave in $\phi\phi$).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

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

COMPARISON WITH SLAC MK III 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 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

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}

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 $\pi^- p \to K^0_S K^0_S n$ 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[5] reported that in J/ψ radiative decay they observe several hundred $\phi\phi$ which they conclude have $J^{PC} = 0^{-+}$ and see no evidence for $J^{PC} = 2^{++}$ $\phi\phi$. In J/ψ radiative decay one would expect the 0^{-+} channel to be strongly enhanced, since the process $J/\psi \to \gamma\eta_c$(virtual) $\to \gamma$ hadrons (with $J^{PC} = 0^{-+}$) would be expected to be strongly 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 virtually all $\pi^-\pi^+ \to G$ and thus only 0^{++}, 4^{++}, 6^{++} .... etc. would be possible. 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. 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 cannot reconcile our experiment, the LASS experiment on $\pi^- p \to K_S^0 K_S^0 \Lambda$, and the MK III data on the 2^{++} channel which contains the f and f' and θ. We find in that analysis that LASS should have seen the θ at a level about half the f' peak. If we leave SLAC MK III data out we can fit all hadronic experiments easily. If we leave LASS data out we can also fit the remaining data but we have not succeeded in fitting both. Meshkov[7] pointed out in his talk although $J^{PC} = 2^{++}$ is assigned to the θ, 0^{++} is not ruled out. If $J^{PC} = 0^{++}$ then our coupled channel analysis which assumed θ has 2^{++} would not be relevant. We leave this as an unresolved problem at present.

What about Meshkov oddballs[6] (Exotic Glueballs)? 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 $\bar{A}$-exchange etc. which can make exotic glueballs can occur. At present only about 5% of our data is in this region 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 will also improve our statistics per unit time in π-exchange. Our goal will be to search for possible Meshkov 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.

SUMMARY

We have gathered and partial-wave analyzed 6658 events of $\pi^- p \to \phi\phi n$, and for maximum precision simultaneously analyzed the small physical background reaction $\pi^- p \to \phi K^+ K^- n$ accompanying the $\phi\phi$. We find the $\phi\phi$ which is OZI-forbidden towers above the $\phi K^+ K^-$ 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 $\phi K^+ K^-$ is mostly structureless background, shows no evidence for resonances and has only 3% $J^{PC} = 2^{++}$ compared to the

$\phi\phi$ which has 100% resonant 2^{++}. We were able to use the coherent 1^{--} wave of the ϕK^+K^- to calculate 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.

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 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 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 cannot understand the absence of the θ in the LASS experiment $K^-p \to K_S^0 K_S^0 \Lambda$.

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