**EVIDENCE FOR A 4th STATE RELATED TO THE THREE
 $J^{PC} = 2^{++}$, $\pi^- p \rightarrow \phi\phi n$ STATES EXPLAINABLE BY 2⁺⁺
GLUEBALL PRODUCTION**

R.S. LONGACRE^a, S.J. LINDENBAUM^{a,b}

^aBrookhaven National Laboratory, Upton, NY 11973, USA

^bCity College of New York, NY 10031, USA

JUNE 2004

Physics Department

Brookhaven National Laboratory

Operated by

Brookhaven Science Associates

Upton, NY 11973

Under Contract with the United States Department of Energy

Contract Number DE-AC02-98CH10886

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state to reflect those of the United States Government or any agency thereof.

Evidence for a 4^{th} state related to the three $J^{PC} = 2^{++}, \pi^- p \rightarrow \phi\phi n$ states explainable by 2^{++} Glueball production

R.S. Longacre^a, S.J. Lindenbaum^{a,b}

^aBrookhaven National Laboratory, Upton, NY 11973, USA

^bCity College of New York, NY 10031, USA¹

Abstract

Four separate experiments(Etkin et al.[1-4]), observing the OZI forbidden disconnected reaction $\pi^- p \rightarrow \phi\phi n$ with increasing statistics were performed, and published in journals over a period of a decade (1978-1988). All have been consistent with each other, and a few much less precise, much lower statistics experiments on the reaction later performed by others. These experiments exhibited very selective complete breakdown of the OZI suppression by 3 $\phi\phi$ resonances with $I^G J^{PC} = 0^+ 2^{++}$ in the observed mass region 2.038 to 2.600 GeV. The only viable proposed explanation has been that the $I^G J^{PC} = 0^+ 2^{++}$ Glueball expected in this mass region caused the hard glue in the disconnection to resonate and very selectively breakdown the OZI suppression for its quantum numbers only. Recently a p p central production spin analysis was found consistent with a single resonance named $f_2(1950)$ with a dominant decay mode $f_2(1270)\pi\pi$ (Barberis et al. [5]). In this letter we examine the evidence whether this is related to the $\phi\phi$ resonances.

1 Introduction

The first critical test of non-perturbative QCD was the prediction of a spectrum of Glueballs(multi-gluon resonant states) by Lattice Gauge Theory(LGT)[6-9]. Even phenomenological work made the existence of Glueballs inescapable.

Unfortunately two decades later there is no consensus on the existence of even one Glueball. Obviously the Glueball spectrum is accompanied by the many other varieties of quark built states and also possibly hybrids. To date LGT assumes pure glue and has not solved the problem of including quarks capable of predicting both spectra, and their mixing. If a Glueball has the same quantum numbers as a quark state which it overlaps in mass, it is expected from quantum mechanics that they would mix and the mixed quark built states would have substantial glue. Thus it became clear that a filter which passes Glueballs or glue rich quark-glue mixed states, and rejects quark built states was extremely desirable for discovering Glueballs, and the accompanying substantially mixed with glue states if they existed.

¹This research was supported by the U.S. Department of Energy under Contract No. DE-AC02-98CH10886 and the City College of New York Physics Department.

The strong interaction OZI disconnected diagram $\pi^- p \rightarrow \phi\phi n$ was proposed and used[1-4] as such a filter. The two hard gluons bridging the disconnection would by OZI suppression reject quark built states. However in a mass region where a Glueball with the quantum numbers contained in the $\phi\phi$ system occurred, the gluons would resonate to form the Glueball, break down the OZI suppression and let the Glueball and mixed quark plus Glueball states pass through. The mass region accessible to the $\phi\phi$ experiment[4] 2 to 2.6 GeV was ideal for detecting the 2^{++} Glueball[6-9].

2 The $\phi\phi$ Resonances and Discussion

The OZI rule was found to be completely broken down, very selectively, in the reaction $\pi^- p \rightarrow \phi\phi n$, by three resonance states with quantum nubers $I^G J^{PC} = 0^+ 2^{++}$. These are the quantum numbers of the 2^{++} Glueball expected[6-9] in this mass region. The $\phi\phi$ production t dependence was sharply peaked forward with the shape consistent with π exchange. This implies that the disconnected light quark lines ended in a $\pi^+ \pi^-$ annihilation bridged by gluons to the strange quark lines of the $\phi\phi$ system. Since π exchange would only allow isoscalar Glueballs ($J^{PC} = 0^{++}, 2^{++}, 4^{++}$). The states were orginally listed as g_t, g'_t, g''_t (are now listed as $f_2(2010), f_2(2300), f_2(2340)$ states) in the PDG summary table as established. They were found to contain approximately 87% of the events in the sample of the $\phi K^+ K^- n$. The $\phi K^+ K^- n$ reaction is OZI allowed, while the $\phi\phi n$ reaction violates OZI and is 7.7 times bigger than the allowed piece. The 13% $\phi K^+ K^- n$ events contain 8.6% structureless and incoherent background, plus 4% $I^G J^{PC} = 1^+ 1^{--}$, and .4% $I^G J^{PC} = 0^+ 2^{++}$ coherent π exchange amplitudes. The π exchange $\phi K^+ K^- n$ amplitudes were slowly varying and were either a non-resonant or broad resonance source. Thus the expected factor ~ 100 suppression has become factor 8 enhancement or factor ~ 800 breaking of the OZI rule. All waves up to J=6 and L=4(114 waves) were searched for and except for one S-wave and two D-waves which contributed to the three 2^{++} $\phi\phi$ resonances, nothing was found. The establised resonance $f_4(2050)$ with $I^G J^{PC} = 0^+ 4^{++}$ which could in priniple be detected, other expected from the quark model, and some reported but not established were not detected. As stated above the t dependence showed that the three 2^{++} $\phi\phi$ resonances where produced by annihilation of the incident π^- and a exchange π^+ to form the gluon bridge across the disconnection to the $\phi\phi$ final state. The annihilating pions contain only u and d quarks and the $\phi\phi$ is practically all s and $\bar{s}$ quarks, except for the very small contribution due to the very small departure from ideal mixing. Thus it is a very clean flavor changing example. Fig.1 explains the powerful selectivity of the $\phi\phi$ system since in addition to the Gottfried-Jackson and Trieman-Yang angles, the polar(θ) and azimuthal angles(α) of each ϕ gave six angles and their correlations which yield the enormously selective signature for each wave, examples of which are shown.

Reference [4] concluded the OZI suppression was broken down by one primary 2^{++} Glueball mixing with two quark states. The very strong glueball mixing effects on the quark states, which are not yet known, are likely to change the character of these mixed states drastically. Hence attempts to identify these states via the quark model calculations appear unjustified. The OZI rule argument has been attacked unsuccessfully by a number of theorists[10, 11]. However, to our knowledge, except for J = 0 where vacuum mixing could introduce flavor

changing, the OZI rule works experimentally in all strong interaction cases where there is clean flavor changing annihilation between the initial and final states, except where glue type resonances occur. It was also shown that by comparing $K^- p$ and $\pi^- p$ interactions that the OZI rule was more or less entirely broken down in $\pi^- p \rightarrow \phi\phi n$ [12] in the mass region investigated. It would require a flavor changing resonance to do this for $J > 0$, and a Glueball is the naturally expected choice. No other viable explanation of our data has occurred since the initial results in 1982 [2].

3 Is The $p p$ Central Production Related ?

We now consider the evidence that a 4^{th} state may be related to the above $\phi\phi$ experiment and analysis[4]. Reference [5] studied 4 π channels in central $p p$ interactions at 450 GeV/c. Their fig 1b shows a broad mass spectrum in the mass of $4\pi^0$ which they consider likely to be least affected by other effects. In a spin analysis they conclude in fig 1e that the broad mass spectrum is $I^G J^{PC} = 0^+ 2^{++}$ decaying via a $f_2(1270)\pi\pi$ in a overall S-wave to $4\pi^0$. Fig 3f shows the same $I^G J^{PC} = 0^+ 2^{++}$ $f_2(1270)\pi\pi$ wave in the $2\pi^+ 2\pi^-$ channel, which has the most statistics. They concluded that their analysis was consistent with one $f_2(1270)\pi\pi$ resonance with a mass of 1950 MeV. It is the $I^G J^{PC} = 0^+ 2^{++}$ $f_2(1270)\pi\pi$ wave that we would like to determine whether it could be related to previous $\phi\phi$ work[4].

First we considered the possibility of fitting our $\phi\phi$ resonances together with the $I^G J^{PC} = 0^+ 2^{++}$ $f_2(1270)\pi\pi$ wave of Ref[5]. By considering only three poles which was what we found sufficient in our $\phi\phi$ work. Our best fit was an unacceptable 9σ fit. One should keep in mind here that the physical mass spectrum of the $\phi\phi$ system was cut off at 2.038 GeV, so one could not experimentally measure below this value. However the lowest(2.010 GeV) $\phi\phi$ resonance width of 200 MeV extended below the threshold by 130 MeV. However when we introduced a 4^{th} pole, we obtained a good 2σ fit for the $\phi\phi$ and the new $f_2(1270)\pi\pi$ data[5] combined. This new data has the same $I^G J^{PC} = 0^+ 2^{++}$ quantum numbers as the $\phi\phi$ resonances, thus implying there is reasonable evidence suggesting they are related. In this fit the structure that appears around 2.4 GeV in both data sets connects the two systems(Fig.2-3). Requiring an additional pole does not change our previous Glueball interpretation presented in Ref[4]. The number of Glueballs plus Glueball + quark mixed states cannot be determined in LGT without including quark loops. However having a 2^{++} Glueball was the only viable explanation for the data obtained in 1982 [2]. Nothing which has occurred in the two decades since contradicts this, but instead strengthens the case[3-4,10-12].

Now let us consider the details of the four pole fit. We have extracted the resonance parameters corresponding to each of the four poles which are displayed in Table 1.

Table I - Resonance parameters				
Mass(GeV)	Width(GeV)	S_2	D_0	D_2
$2.049^{+0.035}_{-0.024}$	$.567^{+0.064}_{-0.071}$	$96\%^{+4}_{-10}$	$1\%^{+7}_{-1}$	$3\%^{+9}_{-3}$
$2.123^{+0.015}_{-0.033}$	$.294^{+0.056}_{-0.055}$	$89\%^{+7}_{-11}$	$2\%^{+13}_{-2}$	$9\%^{+10}_{-8}$
$2.340^{+0.013}_{-0.013}$	$.148^{+0.066}_{-0.032}$	$7\%^{+15}_{-7}$	$12\%^{+14}_{-10}$	$81\%^{+3}_{-14}$
$2.412^{+0.028}_{-0.032}$	$.362^{+0.100}_{-0.053}$	$45\%^{+28}_{-7}$	$21\%^{+7}_{-19}$	$34\%^{+15}_{-20}$

The first resonance best fit mass is barely above the lower boundry of the $\phi\phi$ mass region, but due to the large width of the pole and its errors it could easily be below. The other three resonances are clearly in the $\phi\phi$ mass region. The 2nd resonance seems similar to our previously obtained $f_2(2010)$. It is approximately 89% S-wave, but is shifted to higher mass by about 100 MeV and is wider. The 3rd resonance is similar to our previously obtained $f_2(2300)$ shifted upward by about 40 MeV, but well within the errors. The width is the same and it is about 95% D-wave consistent with the previous case. The 4th resonance is similar to our previous $f_2(2340)$. However there are some differences in the division of the D-wave into the S=0 and S=2 states in the 3rd and 4th resonances.

Fig.2 shows the $I^G J^{PC} = 0^+ 2^{++}$ $f_2(1270)\pi\pi$ mass spectrum, where the solid line is the 4 resonance fit given in Table I, and the dashed line is the 3 resonance fit. The dotted curve will be explained in the next section. Fig.3 shows the $I^G J^{PC} = 0^+ 2^{++}$ spin 2 S-wave $\phi\phi$ mass distribution. Again the solid line is the 4 resonance fit given in Table I, where the dashed line is the 3 resonance fit. This is true for all Figs.2-7. Fig.4 shows the $I^G J^{PC} = 0^+ 2^{++}$ spin 0 D-wave $\phi\phi$ mass spectrum. Fig.5 shows the $I^G J^{PC} = 0^+ 2^{++}$ spin 2 D-wave $\phi\phi$ mass spectrum. The S-wave was used as a phase reference. Fig.6 shows the 2⁺⁺ spin 0 D-wave phase relative to the S-wave as a function of $\phi\phi$ mass. Fig.7 shows the 2⁺⁺ spin 2 D-wave phase. The three resonance fit gives a very crude qualitative agreement, but must be discarded as it fails quantitatively by 9 σ , whereas the four resonance fit is a 2 σ fit.

Fig.8 shows the argand diagram for the $I^G J^{PC} = 0^+ 2^{++}$ $f_2(1270)\pi\pi$ amplitude. The argand diagrams for the three $I^G J^{PC} = 0^+ 2^{++}$ $\phi\phi$ amplitudes are shown in Fig.9. These argand diagrams show clear resonance behavior. The fact that the four resonance fit is a good fit which ties together the structure in the $f_2(1270)\pi\pi$ and the $\phi\phi$ structure near 2.4 GeV, while retaining the basic characteristics of the original three $\phi\phi$ resonance states implies it is likely they are related, and due to the same Glueball and mixing mechanism which explains the $\phi\phi$ states.

4 Suppose they are not related

We can obtain a four resonance fit and have no relationship between the resonance in $f_2(1270)\pi\pi$ and the three $\phi\phi$ resonances. We show in Fig.2-7 as a dotted line the four resonance in which there is no connection between $f_2(1270)\pi\pi$ and $\phi\phi$. The $\phi\phi$ data contains additional statistics obtained beyond [4] and a new analysis which is consistent [4]. This fit is a 6 σ fit, where the most of the σ 's arises from Ref[5] not fitting the structure in their data near 2.4 GeV which overlapped with the $\phi\phi$ mass region. One could add a second

resonance in the $f_2(1270)\pi\pi$ or attribute that to some other effect. However even if one assumes that the $f_2(1270)\pi\pi$ is not related to the $\phi\phi$ that in no way contradicts the conclusions drawn on the basis of the $\phi\phi$ resonances data. Thus in the two decades of physics work following the initial strong evidence explainable only with the effects caused by a 2^{++} Glueball, all that occurred both in extension of that work, and all other relevant works both experimental and theoretical in the region of 2 GeV mass, has strengthened the initial evidence. Nothing published has successfully contradicted it, or produced a viable alternative explanation of our investigations.

A much quoted classic paper on the LGT Glueball mass spectrum by Moringstar and Peardon[9] using SU(3) pure gauge theory finds that there can be Glueball states consisting of one to several Glueballs degenerate in mass. However their investigations conclude the multi-glueball states would be high enough in mass so that the predicted lowest lying $I^G J^{PC} = 0^+ 2^{++}$ Glueball would be a single Glueball which could mix with quark-built states in the ~ 2 GeV mass region. The mass they determined for the 2^{++} Glueball is $2.40 \pm .15$ GeV which is consistent with the $\phi\phi$ resonance data.

A recent discussion on the $\phi\phi$ resonance states with Michael Creutz led to a private communication he sent us, from which we quote since it should be of interest to the readers. "I am glad to hear that you are continuing to pursue the $\phi\phi$ states as Glueball candidates. I personally believe that these states are indeed likely to contain substantial glue, although I expect there will be some mixing with quark states as well. This mixing will make a complete analysis very complicated, but the glue component should exist and will appear in all the states that are mixed"[13].

5 Conclusion

The breakdown of the OZI suppression by a factor ~ 800 is enormous. It is strikingly extremely selective since only the three $\phi\phi$ resonances all of which have $I^G J^{PC} = 0^+ 2^{++}$, the quantum numbers of the 2^{++} Glueball, and nothing else is found in the analysis up to $J=6$ and $L=4$ (114 waves) in a mass region consistent with the predicted 2^{++} Glueball mass. This has only been explained by a glue resonance(2^{++} Glueball). No other viable alternative has been published in two decades since the initial results in 1982[2] which have been strengthened with time[1-4]and [10-13]. The 450 GeV/c pp central production results of [5] are explainable by a simple extension of our previous $\phi\phi$ resonance analysis[4].

References

- [1] A. Etkin et al., Phys. Rev. Lett. 41 (1978) 784.
- [2] A. Etkin et al., Phys. Rev. Lett. 49 (1982) 1620.
- [3] A. Etkin et al., Phys. Lett. B 165 (1985) 217.

- [4] A. Etkin et al., Phys. Lett. B 201 (1988) 568.
- [5] D. Barberis et al., Phys. Lett. B 471 (2000) 440.
- [6] G. Balli et al., Phys. Lett. B 309 (1993) 378.
- [7] C. Michael and M. Teper, Nucl. Phys. B 314 (1989) 347.
- [8] B. Berg and A. Billoire, Nucl. Phys. B 221 (1983) 109; B 226 (1983) 405.
- [9] C. J. Morningstar and M. Peardon, Phys. Rev. D 60 (1999) 034509.
- [10] S.J. Lindenbaum and R.S. Longacre, Phys. Lett. B 165 (1985) 202; Phys. Lett. B 234 (1990) 163.
- [11] S.J. Lindenbaum, Comm. Nucl. Part. Phys. 13 (1984) 285; in Superstrings, Supergravity and Unified Theories, The ITCP Series in Theoretical Physics Vol 2(World Scientific, Singapore, 1986) pp 548-593.
- [12] C. Landberg et al., Phys. Rev. D 53 (1996) 2839.
- [13] Michael Creutz, Private Communication.

Figure 1: Above we show 6 out of the 114 waves tried in our $\phi\phi$ partial wave analysis. We show projections of the pure waves along: column 1 the ϕ azimuthal decay angle(α); column 2 the sum of azimuthal decay angles for ϕ_1 and ϕ_2 ; column 3 the difference; column 4 the cosine of the Gottfried Jackson angle(β); column 5 the cosine of the polar ϕ decay angle(θ); column 6 the sum of the cosines of the polar decay angles of ϕ_1 and ϕ_2 ; column 7 the difference.

Figure 2: The $I^G J^{PC} = 0^+ 2^{++} f_2(1270) \pi \pi$ mass spectrum from Ref.[5]. The solid curve is the four resonance fit(table I); dashed curve is a three resonance fit; and dotted curves is a separate three resonance fit to the three $\phi\phi$ waves, and a separate fit with one resonance to the $f_2(1270) \pi \pi$ wave.

Figure 3: The $I^G J^{PC} = 0^+ 2^{++}$ spin 2 S-wave $\phi\phi$ mass spectrum. The solid, dashed and dotted curves are three fits described in Figure 2 and the text.

Figure 4: The $I^G J^{PC} = 0^+ 2^{++}$ spin 0 D-wave $\phi\phi$ mass spectrum. The solid, dashed and dotted curves are three fits described in Figure 2 and the text.

Figure 5: The $I^G J^{PC} = 0^+ 2^{++}$ spin 2 D-wave $\phi\phi$ mass spectrum. The solid, dashed and dotted curves are three fits described in Figure 2 and the text.

Figure 6: The $I^G J^{PC} = 0^+ 2^{++}$ spin 0 D-wave $\phi\phi$ phase measured with respect to the $I^G J^{PC} = 0^+ 2^{++}$ spin 2 S-wave. The solid, dashed and dotted curves are three fits described in Figure 2 and the text.

Figure 7: The $I^G J^{PC} = 0^+ 2^{++}$ spin 2 D-wave $\phi\phi$ phase measured with respect to the $I^G J^{PC} = 0^+ 2^{++}$ spin 2 S-wave. The solid, dashed and dotted curves are three fits described in Figure 2 and the text.

Figure 8: The $I^G J^{PC} = 0^+ 2^{++} f_2(1270) \pi \pi$ argand amplitude generated by four resonance fit. Each * is at 0.1 GeV markings, starting with 1.5 GeV.

Figure 9: The $I^G J^{PC} = 0^+ 2^{++} \phi\phi$ argand amplitude for spin 2 S-wave(S_2), for spin 0 D-wave(D_0), and for spin 2 D-wave(D_2) generated by four resonance fit. Each * is at 0.1 GeV markings, starting with 2.1 GeV.