Reaction $\pi^- p \to \varphi\varphi n$ and Evidence for Glueballs

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The authors have detected 1203 events of the reaction $\pi^- p \to \varphi\varphi n$ at 22 GeV/c, and have performed a partial-wave analysis of the $\varphi\varphi$ system. The results are well represented by two resonances, both with quantum numbers $I^G = 0^+$, $J^{PC} = 2^{++}$. The breakdown of the Okubo-Zweig-Iizuka suppression observed in this reaction is naturally explained in the context of QCD if these states are considered to be glueball candidates.

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In a prior experiment[1] we studied the reactions (1) $\pi^- p \to K^+K^-K^+K^- n$, (2) $\pi^- p \to \varphi K^+K^- n$, and (3) $\pi^- p \to \varphi\varphi n$. We observed about 100 events of reaction (3) and found that although reaction (3) is Okubo-Zweig-Iizuka (OZI) forbidden, the OZI suppression was absent.[2] A reasonable interpretation of this result was the intervention of multigluon resonances (glueballs) which could break down the OZI suppression.[2] In fact, the OZI suppression of φ's produced by pions makes reaction (3) an excellent place to search for glueballs. The $\varphi\varphi$ system has $I^G = 0^+$ and $C = +$. The present experiment has obtained sufficient statistics for a meaningful partial-wave analysis to identify explicit glueball candidates.

This experiment[3] was performed in a 22-GeV/c, unseparated, negative beam from the Brookhaven National Laboratory alternating-gradient synchrotron. The analysis is based on 1203 events of reaction (3) detected with the spectrometer MPS II.[4] The configuration of the apparatus and the trigger requirements correspond very closely to those used in the earlier measurement.[1] The major change was the replacement of all the spark-chamber detectors by 45 planes of narrow-cell drift chambers. These chambers permitted an approximately tenfold increase in pion flux over the earlier experiment and have better resolution than the spark chambers. The second significant change was the use of an improved veto box to detect large-angle charged particles or photons from the target. This analysis is based on the subset of triggers having no signal in the target veto box.

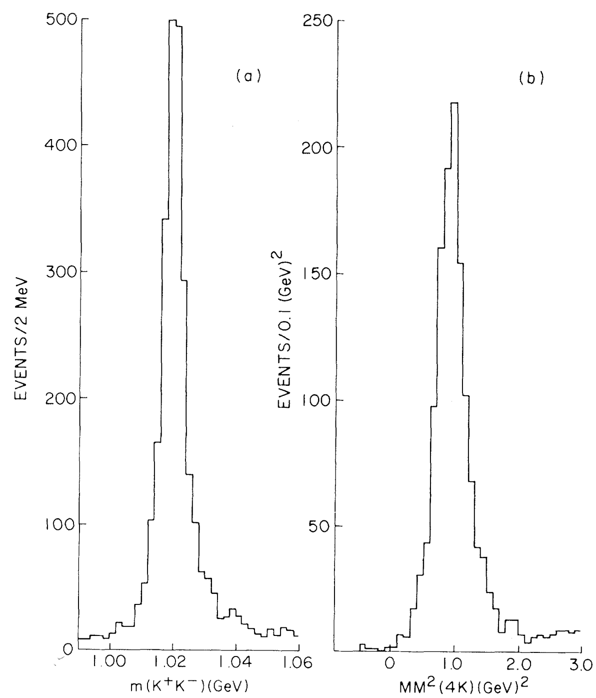

FIG. 1. (a) K^+K^- effective-mass plot for the second pair when the first pair falls in the φ mass band (1019.6 ± 14 MeV). (b) Missing mass squared from the $\varphi\varphi$ system.

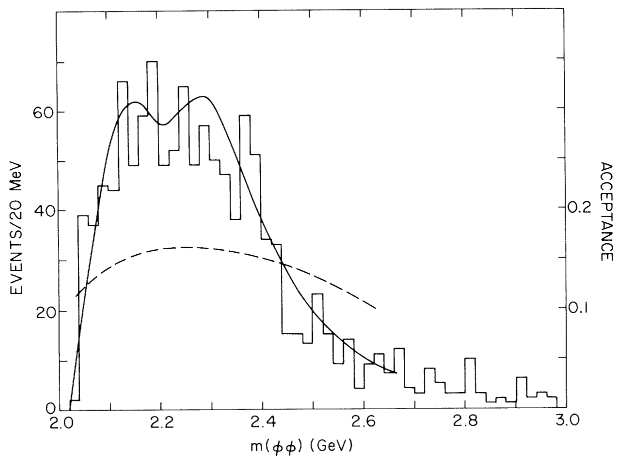

FIG. 2. Observed $\varphi\varphi$ effective-mass distribution (histogram) with that calculated from the fit described in the text (solid line). Shown also is the effective-mass dependence of the experimental acceptance (dashed line).

In Fig. 1(a) is plotted the mass of the other K^+K^- pair in an event whenever one K^+K^- pair falls in the φ mass band (1019.6 ± 14 MeV). The prominence of the double φ signal noted in the earlier measurement[1] is seen again here. This prominence strikingly indicates the breakdown of the OZI suppression.[2] The resolution improvement of MPS II is indicated by the width of the φ peak, ≈ 8 MeV [full width at half maximum (FWHM)] versus 14 MeV in Ref. 1. Figure 1(b) shows the square of the missing mass from the events with two φ mesons, showing a well-defined neutron peak, N^* recoils having been effectively removed by the veto box. Selection of events with $0 < \mathrm{MM}^2 < 1.6$ GeV^2 yields 1203 events of reaction (3) with an estimated background of 130 events from reaction (2) and 40 events of non-neutron recoil. Figure 2 shows the detected $\varphi\varphi$ effective-mass spectrum and the mass dependence of the Monte Carlo–determined acceptance of the apparatus. This spectrum is consistent with that of Ref. 1 and other subsequent low-statistics results.[5] The t distribution is consistent with $e^{(9.4\pm0.7)t'}$ up to $|t'| \sim 0.3$ GeV^2.

In order to determine the partial waves playing

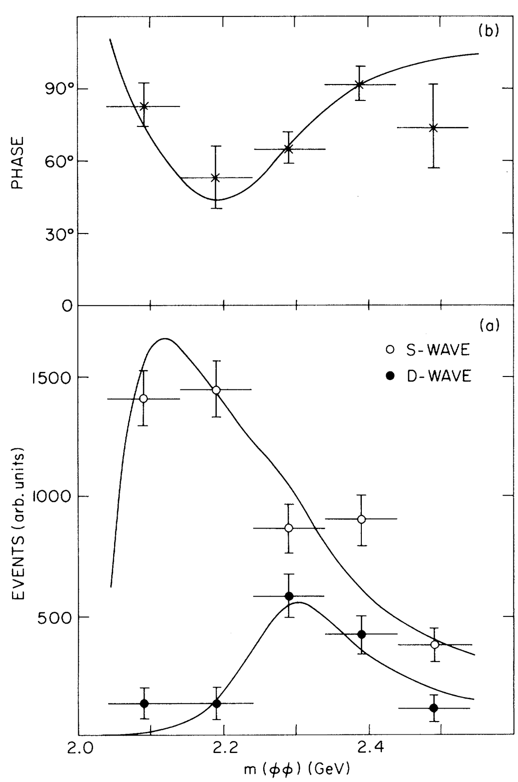

FIG. 3. (a) Intensity and (b) phase difference for the two-wave fits. The curves show the fit by two Breit-Wigner resonances described in the text.

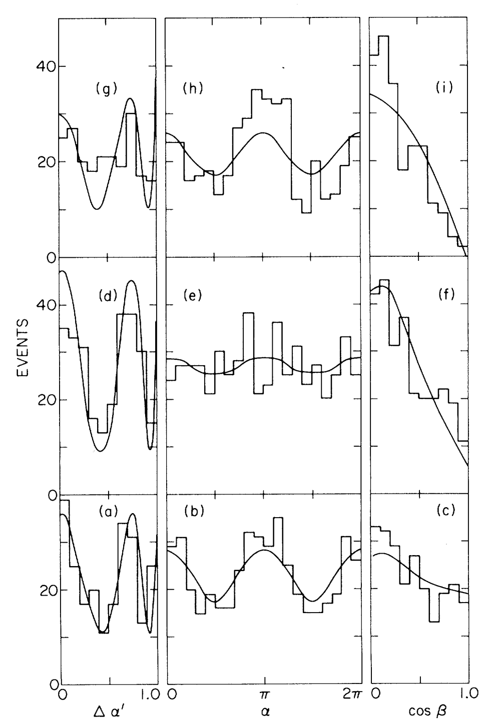

FIG. 4. Angular distributions for three of the 100-MeV mass bins; (a), (b), and (c) 2.04–2.14 GeV; (d), (e), and (f) 2.24–2.34 GeV; (g), (h), and (i) 2.34–2.44 GeV. α, $\Delta\alpha'$, and β are defined in the text. The curves are the two-wave fit modified by the experimental acceptance.

TABLE I. Quantum numbers and parameters of the Breit-Wigner resonances fitted to the S- and D-wave amplitudes of Fig. 3.

	I^GJ^{PC}	Mass (GeV)	Γ_{tot} (GeV)	
$g_T(2160)$	0^+2^{++}	2.16 ± 0.05	0.31 ± 0.07	$\Gamma_D/\Gamma_S \approx 0.02$
$g_T(2320)$	0^+2^{++}	2.32 ± 0.04	0.22 ± 0.07	$\Gamma_S/\Gamma_D \approx 0.04$

a major role in the $\varphi\varphi$ spectrum, the events in the mass region 2.1 to 2.3 GeV were fitted with an incoherent background plus one additional partial wave of specific J^P, L, S, M, and exchange naturality, η. All permitted values for the quantum numbers were tried up to $J=4$ and $L=3$. The largest contribution came from $J^PSLM^\eta = 2^+2\,0\,0^-$. This wave was retained and all others were tried, one at a time, in order to search for the presence of other waves. The only other significant contribution came from $J^PSLM^\eta = 2^+2\,2\,0^-$. The two waves were retained and once again all others tried one at a time. No other significant waves were found. The $\varphi\varphi$ data were then divided into 100-MeV bins in order to explore the mass dependence of the partial-wave structure.[6] The background from φK^+K^- events (~10%) was estimated by examining the regions adjacent to the $\varphi\varphi$ peak. This background was represented by a flat distribution in all angles. A maximum-likelihood fit to the first five bins with use of the two $J^P=2^+$ waves described above gave the S-wave and D-wave amplitudes and the D-S phase difference shown by the points of Fig. 3. We conclude, therefore, that the $\varphi\varphi$ system below 2.5 GeV has a remarkably simple partial-wave structure, being dominated by two waves with $J^P=2^+$, one an S wave and the other a D wave.[7]

In order to assure ourselves that this result is not sensitive to the corrections for the acceptance of the apparatus, we examined the various angular distributions and correlations in the $\varphi\varphi$ decays. The decay of the $\varphi\varphi$ system was characterized by six angles, the Gottfried-Jackson angles $[\beta(\text{polar}),\gamma]$ in the center-of-mass frame, and the polar $(\theta_{1,2})$ and azimuthal $(\alpha_{1,2})$ decay angles of each φ. The most important variables selecting the 2^+ states are α (α_1 and α_2 combined) and $\alpha_1-\alpha_2$. Monte Carlo studies indicate that the shape of these distributions are not affected by the apparatus, unlike the Gottfried-Jackson polar angle, for example, which is very dependent on details of the acceptance. To equalize the phase space in each histogram bin we used instead of $\alpha_1-\alpha_2$ the quantity

$$\Delta\alpha' \equiv [(\alpha_1-\alpha_2)/\pi](1-|\alpha_1-\alpha_2|/4\pi).$$

Figure 4 shows the distributions in $\Delta\alpha'$, α, and $\cos\beta$ for three mass bins compared with the S- and D-wave fits. The other variables have no significant structure and the fit agrees with the data in all bins and variables.[8] We found that a single Breit-Wigner resonance gives an unacceptable ($>10\sigma$) fit to the data in Fig. 3, primarily because of the phase difference. We fitted two interfering Breit-Wigner resonances[9] and obtained the acceptable fit shown by the curves in Fig. 3. The parameters of this fit are listed with all the quantum numbers of the two states in Table I. The effective-mass spectrum computed from this fit is shown as the solid curve in Fig. 2.

In conclusion, we have observed a strong signal in reaction (3) which should be OZI suppressed.[2,10] The $\varphi\varphi$ system is produced peripherally, and the effective mass is concentrated near threshold and falls sharply at a mass of 2.4 GeV. The partial-wave structure is extremely simple, being dominated by two $J^{PC}=2^{++}$ states, and the data are well-described by nearly orthogonal Breit-Wigner resonances. Within the context of QCD a natural explanation of these results is that the states observed are new resonances, largely composed of gluons, which are thus not subject to the OZI rule. Thus these states imply the presence of one or more primary glueballs[11] in this region and hence are glueball candidates.

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[5]T. A. Armstrong *et al.*, Nucl. Phys. B196, 176 (1982); C. Daum *et al.*, Phys. Lett. 104B, 246 (1981). The narrow enhancement in φ pairs produced from Be reported in the latter paper is not confirmed by higher-statistics results reported by C. Daum *et al.*, in Ref. 3, and by B. R. French *et al.*, in Ref. 3.

[6]The bin size was chosen because about 200 events per bin are needed to obtain reliable solutions.

[7]One might expect a background of the $L = 0$, $J^P = 0^+$ wave at threshold, but this wave contributes only (10 $\pm$ 5)% of the events in the lowest-mass bin.

[8]For more details of the analysis, see S. J. Lindenbaum, in Proceedings of the International School of Subnuclear Physics, Course XX, Gauge Interactions, Theory and Experiment, Erice, August 1982 (to be published).

[9]The threshold behavior is taken from R. S. Longacre, Phys. Rev. D 26, 82 (1982).

[10]A recent experiment [T. Armstrong *et al.*, CERN Report No. CERN EP/82-103, 1982 (unpublished)] found the OZI-allowed reaction $K^-p \to \varphi\varphi\Lambda/\Sigma^0$ to have 4 times the cross section of reaction (3). This ratio is substantially less than the ratio of 60 observed in single-φ production by kaons versus pions, and consistent with data on kaon-induced $\varphi\varphi$ production from the present experiment. In addition, the $\varphi\varphi$ effective mass for the kaon-produced events is spread over a very broad range, unlike the data of Fig. 2. This is further evidence that OZI suppression is not present in reaction (3).

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