A HIGH STATISTICS STUDY OF THE $\phi\phi$ MASS SPECTRUM

P.S.L. Booth¹, L.J. Carroll¹, R.A. Donald¹, D.N. Edwards¹, D. Frame^{2(*)},
B.R. French³, M.A. Houlden¹, I.S. Hughes², J.N. Jackson¹,
P.A. Kilcoyne^{1(**)}, J.C. Lassalle³, J.E.T. Lewis^{1(***)}, J.G. Lynch²,
D.McL. McFadzean²⁽⁺⁾, J.J. Myerscough¹, W.H. Range¹,
J.A. Richardson¹⁽⁺⁺⁾, A.S. Thompson², I.R.M. Thompson²⁽⁺⁺⁺⁾,
R.M. Turnbull²

- ¹ University of Liverpool, Department of Physics, Liverpool, UK
² University of Glasgow, Department of Natural Philosophy, Glasgow, UK
³ CERN, European Organization for Nuclear Research, Geneva, Switzerland

ABSTRACT

Results from an experiment studying inclusive $\phi\phi$ production in 85 GeV/c π^- Be interactions are reported. The experiment was designed to search for states of width $\Gamma \lesssim 100$ MeV decaying to $\phi\phi$. A $\phi\phi$ mass spectrum of 13088 $\phi\phi$ events is presented in which it is found necessary to introduce two Breit-Wigners to adequately describe the spectrum shape. The masses and widths were determined to be

$$M_1 = 2231 \pm 10 \text{ MeV}/c^2, \quad \Gamma_1 = 133 \pm 50 \text{ MeV}/c^2$$
$$M_2 = 2392 \pm 10 \text{ MeV}/c^2, \quad \Gamma_2 = 198 \pm 50 \text{ MeV}/c^2.$$

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- (*) Now at Britoil, Glasgow, Scotland
(**) Now at Scicon, London, England
(***) Now at Schlumberger, Strasbourg, France
(+) Now at Forth Research and Development, Stirling, Scotland
(++) Now at Rutherford Appleton Laboratory, England
(+++ Now at YARD, Glasgow, Scotland

1. INTRODUCTION

It has been emphasized by many authors [1-3] that $\phi\phi$ spectroscopy offers a favourable hadronic channel in which to search for the decay of high mass states such as gluonia, η_c mesons and exotic states with $C = +1$. The experimental backgrounds are minimised in this channel since the ϕ is a narrow state, and it may be argued that the production of two ϕ mesons in non-strange hadronic interactions is inhibited by the Okubo-Zweig-Iizuka (OZI) rule [4].

The $\phi\phi$ mass spectrum has been studied in the past in both inclusive and exclusive channels. Both the exclusive experiments [5-7] reporting the observation of the reaction $\pi^- p \rightarrow \phi\phi n$ and the inclusive measurements [8-11] indicate an excess of $\phi\phi$ events above the number expected for uncorrelated production of two ϕ mesons. If the mechanism for this apparent OZI violation involves gluon exchange, the $\phi\phi$ system could be a promising place to search for states strongly coupled to glue and this was the motivation of the present experiment.

The data to be presented here were obtained by triggering on the inclusive reaction $\pi^- Be \rightarrow K^+ K^+ K^- K^- + X$ at 85 GeV/c. An analysis of 4.1 million events recorded with a "basic" trigger has been reported in a previous paper [12]. The present paper reports the results obtained from 14.7 million triggers with a "high mass" trigger designed to be more selective for high mass $\phi\phi$ events and which resulted in 13088 "true" $\phi\phi$ events.

2. EXPERIMENTAL ARRANGEMENT

The data were obtained in experiment WA67 at the CERN SPS. A beam of 85 GeV/c π^- with an instantaneous intensity of 1.3×10^7 π^- per second was incident on a beryllium target consisting of five segments each of 2 cm thickness, equivalent in total to 16% interaction length for π^- . The resulting interactions were detected in the Ω' spectrometer with a downstream detection and identification system for charged particles (fig. 1). The spectrometer was run with a central magnetic field of 1.35 T. The vertex detector consisted of MultiWire Proportional Chambers (MWPC) followed by two drift chamber modules (D1, D2). The downstream detector consisted of scintillation counter hodoscopes H1, H2 and H3

together with multicell Cerenkov counters C1 and C2 which were filled with Freon 114 and CO₂ respectively. The thresholds for $\pi/K/p$ were 2.8/9.8/18.8 GeV/c for C1 and 5.0/17.4/33.0 GeV/c for C2. The hodoscopes and Cerenkov counters were separated about the median plane for triggering purposes.

A kaon candidate was selected by imposing correlations between the hodoscope elements and Cerenkov counters using MBNIM electronics [13]. A slow kaon (2.8-9.8 GeV/c) was signalled by the correlation H1.H2. $\overline{C1}$, while a fast kaon (9.8-17.4 GeV/c) produced the correlation H1.H2.H3.C1. $\overline{C2}$. An "OR" of these two conditions defined a kaon candidate. The full trigger for the data described in ref. [12] demanded $\geq 2K^+$ and $\geq 2K^-$ and gave an overall selectivity of 5×10^{-4} per interaction.

In order to study the high mass $\phi\phi$ spectrum with greater sensitivity the additional requirement that one K^+K^- pair was above the median plane when the second K^+K^- pair was below the median plane was demanded. This condition reduced the acceptance for low mass $\phi\phi$ pairs and thus biased the data towards high mass increasing the selectivity to 1.5×10^{-4} events per interaction. A total of 14.7 million events was recorded using this trigger.

3. DATA SELECTION

The data have been processed using a modified version of the pattern recognition and geometry program, TRIDENT [14]. The modification allowed a fast offline selection of events having at least four trigger track candidates in the last four MWPC before the drift chambers. A track candidate was defined as a sequence of at least three space points in the MWPC which agreed with the extrapolated predictions using the information on the trigger tracks obtained from the downstream spectrometer. This procedure selected the good 4K trigger candidates coming from the target volume. These events, which constituted about 30% of the total triggers, were then processed by the full pattern recognition and geometry program. In addition, the track candidates found in the MWPC served as a starting point for the pattern recognition.

The first selection imposed on each reconstructed event was that four trigger tracks gave tracing agreement with the hits in the hodoscopes. Kaons were then selected by using the signatures in the two Cerenkov counters, together with the particle momenta. Particles giving no light in C1 with momenta in the range 2.8-9.8 GeV/c were classified as kaons, although there is an ambiguity with protons in this sample. Particles in the range 9.8-17.4 GeV/c giving light in C1 but not in C2 were unambiguous kaons. Finally it was demanded that all four identified kaons were attached to the primary vertex.

4. DETERMINATION OF A "TRUE" $\phi\phi$ MASS SPECTRUM

The $\phi\phi$ candidate events were selected from the scatter plot formed by plotting the effective mass of K^+K^- pairs on the two axes (fig. 2). The ϕ bands may be seen clearly, together with an enhancement where the mass of both K^+K^- pairs is near the nominal ϕ mass of $1.0196 \text{ GeV}/c^2$. The processes contributing to the data in this region are the production of (a) $\phi\phi$, (b) ϕK^+K^- , and (c) $K^+K^+K^-K^-$. It should be noted that the ambiguity between slow kaons and baryons will not contaminate the resonant ϕ and $\phi\phi$ signals but will give contributions to the background processes (b) and (c).

The data were fitted using the parameterization

$$N(i,j) = B(i,j)[N_{\phi\phi}(i,j)BW(i)BW(j) + N_{\phi}(i,j)(BW(i) + BW(j)) + N_B(i,j)]$$

where

- $N(i,j)$ represents the number of events in the (i,j) th bin of the scatter plot,
- $B(i,j)$ is a smoothly varying function representing phase space and acceptance,
- $BW(i)$ is a P-wave Breit-Wigner of fixed width, $\Gamma = 4.1 \text{ MeV}/c^2$ but variable central mass which is smeared by a mass resolution function of variable width,
- $N_{\phi\phi}(i,j)$, $N_{\phi}(i,j)$ and $N_B(i,j)$ represent the contributions from processes (a), (b) and (c) respectively to each bin.

The parameters describing the shape of the function $B(i,j)$ were found by fitting over the mass range $0.98-1.18 \text{ GeV}/c^2$. The number of $\phi\phi$ events was then determined by fitting over the mass range $0.99-1.05 \text{ GeV}/c^2$. The value for the ϕ mass obtained from the fit was $1.0195 \text{ GeV}/c^2$, and the experimental width (FWHM) was $9.1 \text{ MeV}/c^2$. The number of "true" $\phi\phi$ events above the uncorrelated backgrounds (b) and (c) was 18176 ± 356 (overall χ^2 of 1025 for 835 degrees of freedom).

In order to obtain a mass distribution of $\phi\phi$ events, a more restricted $\phi\phi$ bin was selected with limits 1.01 to $1.03 \text{ GeV}/c^2$ on both axes. The effective mass of the K^+K^- pairs in this bin is shown as the upper histogram in fig. 3. The 25461 events thus selected comprise 13088 "true" $\phi\phi$ events with background contributions of 8494 ϕK^+K^- events and 3879 $K^+K^+K^-K^-$ events, the relative contributions being derived from the fit. The mass spectrum for the background contribution, which has to be subtracted from the spectrum of fig. 3 in order to have the "true" $\phi\phi$ mass spectrum, was derived in the following way. Two guard bands around the $\phi\phi$ bin were defined, namely the outer band ($0.99-1.00, 1.04-1.05 \text{ GeV}/c^2$ on both K^+K^- axes) and the inner band ($1.00-1.01, 1.03-1.04 \text{ GeV}/c^2$ on both K^+K^- axes). The $2K^+2K^-$ mass spectrum was then formed imposing the ϕ mass on each K^+K^- pair so that the threshold mass would be the same for the guard band spectra as for the events in the $\phi\phi$ bin. In each of these guard band spectra account was taken of the relative proportion of ϕK^+K^- and $2K^+2K^-$ events in the guard band under consideration and the proportions of ϕK^+K^- and $2K^+2K^-$ events computed to exist in the $\phi\phi$ bin. On comparing the two guard ring spectra they were found to be similar with no systematic deviations occurring in any mass region. We therefore felt confident in assuming that these spectra represent a "true" description of the background in the $\phi\phi$ bin. The inner guard ring mass spectrum was then smoothed by fitting a parameterization used by Granet et al. [15]

$$d\sigma/dM = A(M - M_T)^B \exp(-CM - DM^2)$$

where A, B, C, D and M_T are adjustable constants ($\chi^2/\text{No. of degrees of freedom (N.D.)} = 64/68$). The fit is good with no local deviations and is shown as the full line curve of fig. 3. Thus this parameterization, as is already known [15], describes the mass spectra well. Subtraction of this smoothed background from the total $\phi\phi$ mass spectrum shown in fig. 3 results in the "true" $\phi\phi$ mass spectrum, uncorrected for acceptance, shown in fig. 4(a).

5. ACCEPTANCE

Simulations of $\phi\phi$ production were performed using various physics models for the generation process. The Monte-Carlo calculation includes the effects of the geometric acceptance including the momentum window of the Cerenkov counters, the restrictions imposed by the trigger, the decay and absorption of the secondary kaons, the efficiencies of the scintillation counter hodoscopes and Cerenkov counters, multiple scattering, energy losses and beam absorption. The various physical models for generating two ϕ 's are listed below.

5.1 Uncorrelated $\phi\phi$ model

In this model each ϕ was generated independently with

$$d\sigma/dx_F \propto (1 + 0.05 \exp(33 x_F^2))^{-1}$$

and

$$d\sigma/dp_T^2 \propto \exp(-1.6 p_T - 1.3 p_T^2)$$

These parameterizations represent the distributions for inclusive ϕ production and were obtained from a sample of data taken triggering on $\geq 1K^+$ and $\geq 1K^-$ covering a range in x_F of 0 to 0.4 [16]. The effect of possible x_F or rapidity, y correlations could be studied by a variation in this model when the second ϕ was chosen with the desired correlation with respect to the first ϕ .

5.2 Narrow resonance model

To determine the upper limits for the production cross section times branching ratio of a narrow resonance X , $\sigma(X) \cdot BR(X \rightarrow \phi\phi)$, we have used a different model which generates a narrow state X decaying isotropically into two ϕ mesons. For production characteristics we assume the $d\sigma/dx_F$ distribution for ψ mesons found by Badier et al. [17] and

$$d\sigma/dp_T^2 \propto \exp(-1.5 p_T^2)$$

where the constant of 1.5 was chosen for our $\phi\phi$ mass range by interpolation between the values for ϕ and ψ production. The acceptance in this case is shown as a function of mass in fig. 5(a). This acceptance is equally valid for broad resonances, provided that such resonances have the same production characteristics as narrow states.

5.3 η_c model

A state with mass $3 \text{ GeV}/c^2$ was generated according to the $d\sigma/dx_F$ distribution found by Badier et al. [17] for ψ mesons and with

$$d\sigma/dp_T^2 \propto \exp(-0.91 p_T^2)$$

where the coefficient -0.91 was also taken from ref. [17]. Since the η_c is a 0^- particle decaying into four kaons via two ϕ mesons, the expected angular distributions for such a decay were imposed, i.e. a $\sin^2\theta$ distribution for K mesons with respect to the ϕ helicity axis and a $(1 - \cos 2\gamma)$ distribution for the azimuthal angle γ between the decay planes of the two ϕ 's. The overall acceptance for η_c production was found to be 0.038 where a factor of 0.28 arises from geometric effects and the momentum window of the Cerenkov counters and a further factor of 0.64 is introduced by the correlations demanded in the trigger. A detailed breakdown of the various factors leading to the acceptance is shown in table 1.

6. RESOLUTION

A mass resolution function was constructed using the covariance matrices of the tracks fitted by the reconstruction program. In order to obtain good fits to the observed ϕ and K^0 widths it was found necessary to scale the widths of the resolution functions by a factor of 1.6.

This procedure was used to estimate the mass resolution (FWHM) of the $\phi\phi$ system as a function of $\phi\phi$ mass shown in fig. 5(b).

7. RESULTS ON INCLUSIVE $\phi\phi$

In our earlier paper [12] we were able to obtain a good description of the mass spectrum of 3210 $\phi\phi$ events by using either (a) a Monte-Carlo uncorrelated $\phi\phi$ model giving $\chi^2 = 1.28$ per degree of freedom, or (b) a parameterization used by Granet et al. [15] (see above) which fitted the data with $\chi^2 = 0.85$ p.d.f.

Since we have seen that the Granet et al. parameterization is able to provide a good description of the background (fig. 3) we have tried to fit the true $\phi\phi$ spectrum of fig. 4(a) with this parameterization, allowing the constants to vary, over the mass region 2.06 GeV to 3.5 GeV. The fit is bad with $\chi^2/\text{N.D.} = 129/68$. Fits using either an uncorrelated $\phi\phi$ Monte-Carlo or a polynomial function were also unsuccessful. The deviations from the Granet fit are shown in fig. 4(b). Local deviations, which are responsible for the high value of χ^2 , are seen in the mass regions around 2.22 and 2.38 GeV. The contribution from the 2.38 GeV region being the largest we tried a fit to the mass spectrum with a single S-wave Breit-Wigner plus a Granet et al. background. The fit was improved with $\chi^2/\text{N.D.} = 97/65$ but still had a large contribution to χ^2 from the 2.22 GeV region. We therefore refitted using two S-wave Breit-Wigners modified by the acceptance plus a Granet et al. type background and obtained a good fit with $\chi^2/\text{N.D.} = 72/62$ and with no important local deviations remaining (fig. 6). The values for the masses and widths of the Breit-Wigners were determined to be

$$M_1 = 2220 \pm 10 \quad \Gamma_1 = 77 \pm 40 \text{ MeV}/c^2 \text{ (S-wave)}$$

$$M_2 = 2362 \pm 10 \quad \Gamma_2 = 181 \pm 40 \text{ MeV}/c^2 \text{ (S-wave)}$$

We may compare this result with that found by Lindenbaum et al. [18] in an analysis of ~ 4000 $\phi\phi$ events coming from the exclusive channel $\pi^- p \rightarrow \phi\phi n$. Fig. 10 of ref. [18] shows a possible peak in a mass region similar to ours. A more detailed analysis using angular moments enabled the authors to provide evidence for three states

$$M_1 = 2120^{+20}_{-120} \quad \Gamma_1 = 300^{+150}_{-50} \text{ MeV}/c^2$$

$$M_2 = 2220^{+90}_{-20} \quad \Gamma_2 = 200 \pm 50 \text{ MeV}/c^2$$

$$M_3 = 2360 \pm 20 \quad \Gamma_3 = 150^{+150}_{-50} \text{ MeV}/c^2$$

If we identify their two states at 2220 and 2360 MeV/c^2 with those observed in the present experiment then we should refit our data using a mixture of S and D wave for the lower mass state and a D wave for the higher mass state. We then find the following values

$$M_1 = 2231 \pm 10 \quad \Gamma_1 = 133 \pm 50 \text{ MeV}/c^2 \text{ (50\% S, 50\% D-wave)}$$

$$M_2 = 2392 \pm 10 \quad \Gamma_2 = 198 \pm 50 \text{ MeV}/c^2 \text{ (100\% D-wave)}$$

The corresponding production cross sections were determined to be $\sigma(x) \cdot \text{BR}(x \rightarrow \phi\phi) = 7.5$ and $3.8 \text{ } \mu\text{b/Be nucleus}$ for the lower and higher mass states respectively.

Although there is no statistically significant signal in the $\phi\phi$ mass spectrum in the η_c region, analysis of the angular content of the $\phi\phi$ system in the η_c region [19] reveals a signal in the angular moments which can be interpreted as due to the decay of a $J^P = 0^-$ state. This signal is centred at a mass $2.954 \text{ GeV}/c^2$ with a width $\Gamma = 62 \text{ MeV}/c^2$. If we consider the $100 \text{ MeV}/c^2$ mass interval centred at $2.95 \text{ GeV}/c^2$ on the deviation plot of fig. 4(b) we find 45 ± 30 events above background which should be compared to the value of 96 ± 25 required from the analysis of the moments in this region.

8. CONCLUSIONS

The effective mass spectrum of 13088 "true" $\phi\phi$ events above background, extracted from a large data sample of $2K^+2K^-$ events, has been studied. A satisfactory description of the $\phi\phi$ mass spectrum requires the introduction of two Breit-Wigners with masses and widths of

$$M_1 = 2231 \pm 10, \quad \Gamma_1 = 133 \pm 50 \text{ MeV}/c^2$$

$$M_2 = 2392 \pm 10, \quad \Gamma_2 = 198 \pm 50 \text{ MeV}/c^2$$

These values are in agreement with two of the three states reported in ref. [18].

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TABLE CAPTIONS

TABLE 1 Factors per event involving four kaons in acceptance calculation
 for η_c .

TABLE 2 Correction factors per event involving four kaons.

TABLE 1

Geometric effects and Cerenkov momentum windows	0.28
Correlations demanded in trigger	0.64
Kaon absorption	0.69
Kaon decay	0.55
Beam absorption	0.93
Hodoscope efficiency	0.70
Cerenkov counter efficiency	0.86
Overall acceptance	0.038

TABLE 2

(a) Reconstruction efficiency for 4 trigger tracks in the pattern recognition and reconstruction program	0.60
(b) Vertex reconstruction efficiency	0.78
(c) Four kaon detection efficiency due to random vetoing by fast kaons or pions in the Cerenkov counters	0.49
(d) Correction to beam flux due to scaler dead time	1.10
(e) (Branching ratio $\phi \rightarrow K^+ K^-$) ²	0.24

FIGURE CAPTIONS

Fig. 1 Plan view of Ω' spectrometer.

Fig. 2 (a) Scatter plot of the K^+K^- effective mass combinations for $K^+K^+K^-K^-$ events.

(b) A second view of the scatter plot cut along a diagonal.

Fig. 3 Distribution of $2K^+2K^-$ effective mass for events lying in the $\phi\phi$ mass bin of fig. 2(a). The hatched histogram shows the background contribution from ϕK^+K^- and $K^+K^+K^-K^-$ events. The solid curve represents a fit with the parameterization of Granet et al. [15].

Fig. 4 (a) The "true" $\phi\phi$ mass distribution after background subtraction, the solid curve being a fit to the data using a parameterization similar to that of Granet et al. [15].

(b) The residuals obtained by fitting the "true" $\phi\phi$ spectrum of fig. 4(a) with the Granet et al. parameterization.

Fig. 5 (a) Acceptance for two ϕ mesons from the isotropic decay of a particle X, generated as described in the text.

(b) Mass resolution for $X \rightarrow \phi\phi$ (FWHM).

Fig. 6 The "true" $\phi\phi$ mass distribution with fitted Granet et al. background plus two Breit-Wigners.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6