A partial wave analysis of proton-antiproton annihilation above threshold for $\phi\phi$ production in the JETSET experiment

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Abstract. The JETSET experiment (PS202) conducted at CERN was designed to search for gluonic resonances in the mass range between 2.1 and 2.4 GeV using the channel $p\bar{p} \rightarrow \phi\phi$. This channel is OZI suppressed, thus any observed enhancement of the cross section beyond expectations of the OZI rule could indicate possible resonating gluonic degrees of freedom. In fact, the measured cross section is two orders of magnitude beyond OZI expectations. Subsequent spin-parity analyses have suggested a resonance with a dominant $J = 2$ spin component and a parity of $+1$. Recently, another spin-parity analysis has been performed. This analysis includes the possibility of coherent interference with a scalar background. It will be summarized that the overall fit quality improves when coherent interference is included. A dominant spin component of $J = 2$ still emerges but a $J = 4$ component is also present.

1. Introduction
In the JETSET experiment, inflight antiprotons annihilated with protons in a hydrogen-cluster jet target with an incident momentum ranging from 1.1 to 2.0 GeV/c. The channel $p\bar{p} \rightarrow \phi\phi$ is of particular interest since it is OZI suppressed and the measured cross section, $\sim 3.7 \mu b$, is two orders of magnitude beyond OZI expectations. The channel was detected by a $4K$ final state since the $\phi$ mesons decayed inflight via $\phi \rightarrow K^+K^-$. The range of incident momenta lies just above production threshold for $\phi\phi$ ($\sqrt{s} = 2.04 \text{ GeV/c}$). Due to the OZI suppression, any observed enhancement of the cross section might be attributable to the formation of gluonic resonances in the $s$ channel. A compelling possibility is suggested by a Lattice QCD calculation [1] which predicts the Yang-Mills glueball mass spectrum. The lightest tensor glueball with $J^{pc} = 2^{++}$ is expected to lie in the mass range explored by this experiment.

2. Partial wave analysis
To identify the spin and parity of a possible resonance an extensive partial wave analysis has been carried out. Initially, a 3-wave solution was obtained [2]. All three waves had $J^{pc} = 2^{++}$. Changes in the relative phases and a narrow peak in the total cross section of these partial waves pointed toward a Breit-Wigner resonance. A goodness of fit test using the likelihood ratio test indicated that the fit could be improved. A subsequent analysis resulted in an improved fit quality and yielded a 6-wave solution [3]. In addition to $2^{++}$ waves, $4^{++}$ waves gained...
significance. However, the $2^{++}$ waves remained dominant. An open question remained regarding the sensitivity of these results to the treatment of the background. In both cases, the background was modeled using $4K$ phase space. From the fit results, it was noticed that the $2K$ mass distribution showed an enhancement near threshold underneath the $\phi$ peak. Furthermore, the scaler channel, $p\bar{p} \rightarrow f_0f_0$, which is below threshold for $2K$ production has a resonant pole at $1.96 \text{ GeV}/c^2$ and a width of $\sim 0.07 \text{ GeV}$. This width is approximately 10 times the width of the $\phi$ resonance. As a consequence, the $\phi\phi$ peak resides in the peripheral region of the $f_0f_0$ peak on a mass plot. This observation may be related to the enhancement of the $2K$ mass distribution near threshold and gives rise to the possibility of coherent interference between the $\phi\phi$ and $f_0f_0$ channels. The presence of such an interference could be imprinted on the angular distributions contained in the data. For this reason, another PWA has been carried out which includes the possibility of coherent interference between the $\phi\phi$ channel and the scaler background.

3. **PWA method**

Coherent interference between two channels implies that the quantum amplitude $f$ used in the PWA becomes

$$|f|^2 = \left| b_{\phi\phi}(\hat{m}) \sum_{i=1}^{23} a_{\phi\phi}^i H_{i}^{\phi\phi}(\hat{\Omega}) + b_{f_0f_0}(\hat{m}) \sum_{i=24}^{28} a_{f_0f_0}^i H_{i}^{f_0f_0}(\hat{\Omega}) \right|^2 \quad (1)$$

where the narrow width approximation is used to factor the mass and angular dependence in each channel. The summations are over the included partial waves and each wave is associated with a total spin $J$ and parity $P$. Each wave is identified with an unknown amplitude $a_i$ and a known angular amplitude $H_i$.

Parity and charge conjugation of the initial and final states define the allowed waves for the $p\bar{p} \rightarrow \phi\phi$ and $p\bar{p} \rightarrow f_0f_0$ channels. Consideration of all quark multiplets in the mass range probed by this experiment for possible mixing indicated that it was sufficient to include all waves up to $J = 4$ and $L = 4$ in the final state for both channels. This implies a total of 23 waves for the $\phi\phi$ channel and a total of 5 waves for the $f_0f_0$ channel.

3.1. **Log-likelihood**

The data was divided into 12 sets according to $\bar{p}$ momenta and a log-likelihood

$$\mathcal{L} = \sum_{i=1}^{n_{\text{events}}} \ln \left( \frac{d\sigma}{d\Omega} \right) - \Lambda \int d\Omega d\hat{m} \left( \frac{d\sigma}{d\Omega} \right) A \left( \hat{\Omega}, \hat{m} \right) \quad (2)$$

was calculated for each momentum bin. The second term is a normalization integral where $\Lambda$ and $A$ are the luminosity and acceptance respectively. This integral is calculated using Monte Carlo estimators. The function $\mathcal{L}$ is maximized with respect to the real and imaginary components of the amplitudes $a_i$ in order to arrive at a likely solution for the wave amplitudes.

3.2. **Ambiguities**

All essential ambiguities in the function $\mathcal{L}$ are thought to be understood. Since even and odd parity waves cannot interfere for either of the two channels the partial waves divide into even and odd parity sets each having a global phase (continuous invariances). In addition, four discrete sign transformations on the real and imaginary components of $a_i$ leave the differential cross section invariant.

Statistical ambiguities arise from the different angular distributions in the data set, however the acceptance and statistics of this data set are sufficient to eliminate all distinct solutions that correspond to secondary maxima in $\mathcal{L}$. 
3.3. Solution search
The objective was to search for a solution consisting of a subset of waves that provides an adequate description of the data at all momentum points. The criterion for a satisfactory solution was established by the likelihood ratio test

\[ \chi^2 = -2 \ln \left( \frac{\mathcal{L}}{\mathcal{L}_0} \right) \]  

(3)

where \( \mathcal{L} \) is the likelihood for a subset of waves and \( \mathcal{L}_0 \) is the likelihood with all waves free. For a large number of events, the likelihood ratio behaves as a \( \chi^2 \) with \( n_0 - n \) degrees of freedom.

First, baseline fits over all momentum points with all 28 waves free plus 4K phase space were obtained. Next, wave combinations involving only the channel \( p\bar{p} \rightarrow \phi\phi \) were considered. This included fits for all single \( \phi \)-wave plus phase space combinations and then all possible two \( \phi \)-wave plus phase space combinations. The solution likelihoods suggested that the fits could be further improved, hence all possible three \( \phi \)-wave combinations plus background were fitted over all momentum points. This approach differs from the previous searches for a three wave solution since not all three wave combinations were checked in the previous searches. Upon obtaining the best three wave solution, the fit quality at lower momenta indicated that an adequate solution was obtained and that additional waves were not necessary. However, at higher momenta, the fit quality was poorer and indicated that it could be improved with the addition of more waves. This circumstance is compatible with the earlier observations regarding the 2K enhancement near \( \phi \) threshold. As a result, it was suggested that the fit might be improved at the higher momentum points with the addition of a \( f_0 \) wave. Consequently, all four wave combinations involving the best 3-\( \phi \) waves and a single \( f_0 \) wave were fitted over all momentum points. A final solution emerged with an improved fit quality at higher momenta. In fact, the fit quality suggested that it was not necessary to consider the addition of any other waves. Thus, this solution is believed to be an adequate description of the data over all momentum points.

4. Results
The best solution consists of three \( \phi \) waves, \( (2^+_S, 4^+_G, 4^+_G) \), and a single \( f_0 \) wave, \( (2^+_D) \). The subscripts indicate the final state orbital angular momentum, \( L_f \) and total spin \( S_f \). As indicated in the partial wave cross sections, the \( 2^+ \) \( \phi \) wave is dominant.

**Figure 1.** Partial cross section for wave \( 2^+_S \).

**Figure 2.** Partial cross section for wave \( 4^+_G \).
5. Summary

The comprehensive PWA of the JETSET data is characterized by a succession of possible solutions and culminates in a final solution having the best fit quality. On the basis of the likelihood ratio test, this solution implies that coherent interference with the scaler background is a feature of the data and that three $\phi$ waves and one $f_0$ wave are a sufficient description of the data over all momentum points. The partial wave cross sections for the $p\bar{p} \rightarrow \phi\phi$ channel reveal a spin component of $J^P = 2^+$ is dominant, however a $J^P = 4^+$ component is significant. Some phase motion is observed in the $4^+$ waves. A clear narrow structure in the total cross section is not observed in this four wave solution, however it should be pointed out that a narrow peak has been observed in a previous three-wave solution with a pure $J^P = 2^+$ spin structure even though the fit quality is not quite as good. Consequently, it appears that the channel $p\bar{p} \rightarrow \phi\phi$ cannot be adequately described by a simple Breit-Wigner resonance.

References

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