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ABSTRACT

The Jetset experiment (PS202) at LEAR uses a compact detector around a hydrogen cluster jet target to perform spectroscopy of hadronic states in the mass range 1.96 to 2.43 GeV, with emphasis on the reaction $\bar{p}p \rightarrow \phi\phi$. Following two short test runs, analysis has clearly revealed a surprisingly copious production of $\phi\phi$ events. This paper gives a brief introduction to the physics motivation of the experiment and an overview of results from some previous experiments, followed by a description of the Jetset detector and of the analysis that led to a preliminary estimate of 0.2-2.0 μb for the $\bar{p}p \rightarrow \phi\phi$ cross section at a center-of-mass energy of 2.25 GeV.

INTRODUCTION

The non-abelian nature of Quantum Chromodynamics (QCD) suggests that gluons may bind to each other (to form glueballs) as well as to quark-antiquark pairs (forming hybrids or meiktons).¹ In searching for such gluonic resonances the most obvious place to look is in channels that are gluon-rich; one such channel is $\bar{p}p \rightarrow \phi\phi$. The Jetset experiment aims to measure the cross section for formation of $\phi\phi$, as a function of center-of-mass (c.m.) energy, from in-flight annihilation of antiprotons on a hydrogen cluster jet target that has been installed in the LEAR ring at CERN.^{2,3}

The $\phi\phi$ state may be produced in a number of ways, one of which is illustrated in Fig. 1. In this simple model, all of the quarks in the proton annihilate with the corresponding antiquarks in the antiproton to produce a purely gluonic intermediate state, from which $\phi\phi$ is formed. This process, with its disconnected quark lines,

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should be suppressed according to the Okubo-Zweig-Iizuka (OZI) rule; such suppression may, however, be overcome if there is an intermediate resonant gluonic state. Alternatively, the state $\omega\omega$ could be formed directly from the $\bar{p}p$ initial state, with ϕ - ω mixing (since ϕ is not pure $s\bar{s}$) then allowing the production of the $\phi\phi$ state. There is also the possibility of production of an intermediate state such as $\eta\eta$ which, having strong components of u, d and s quarks, could then produce $\phi\phi$. One could even conceive of strange quarks being knocked directly from the proton's "quark sea" to form the ϕ pair.

Fig. 1. A possible path to formation of $\phi\phi$ from $\bar{p}p$.

Several previous experiments have conducted measurements of $\phi\phi$ production. In one of the earliest, Davidson et al. isolated six $\bar{p}p \rightarrow 4K$ events in a bubble chamber over a range of momenta from 1.6 to 2.2 GeV/c.⁴ Of these six, one was a $\phi\phi$ event and four were ϕKK events. The average cross section for $\bar{p}p \rightarrow 4K$ in this energy range was calculated to be $3.8 \pm 1.7 \mu\text{b}$, with the conclusion that the cross section for production of an intermediate $\phi\phi$ state was about 600 nb. At a c.m. energy of 3 GeV, experiment R704 at CERN measured the cross section for $\bar{p}p \rightarrow \phi\phi$ to be just 25 nb.⁵

Perhaps the strongest claims for the observation of "glueballs" associated with $\phi\phi$ production come from experiments using the MPS facility at Brookhaven (BNL), where the process under investigation was $\pi^- p \rightarrow \phi\phi n$.⁶ An excess of $\phi\phi$ events above that expected for uncorrelated production of ϕ pairs was observed, in apparent violation of the expected OZI suppression. The $\phi\phi$ mass spectrum showed an extremely broad structure, from threshold up to about 2.5 GeV, which could only be fit with three $J^{PC} = 2^{++}$ resonances that the authors named g_T , g_T' and g_T'' . Experiment WA67 at CERN also saw a larger than expected production of $\phi\phi$; the mass spectrum again showed a broad structure above threshold, which fit to two broad 2^{++} resonances.⁷ Another production experiment, $pN \rightarrow (\phi\phi)X$, this time at Fermilab, showed a very narrow enhancement in the $\phi\phi$ mass spectrum at 2.125 GeV.⁸ Although consistent with $J^P = 0^+$ or 2^+ , it appeared to be too narrow to be identified with any of the claimed g_T resonances.

Fig. 2. The Jetset detector at LEAR.

In apparent contradiction to the claims of a broad 2^+ structure in $\phi\phi$ production, the Mark III experiment at SLAC showed (in addition to the well-known $\eta_c(2980)$) a fairly broad 0^- structure near 2.2 GeV in the $\phi\phi$ mass spectrum, from the radiative decay $J/\psi \rightarrow \gamma\phi\phi$.⁹ The pseudoscalar nature of this enhancement, which is consistent with production of the $\eta(2100)$, was in agreement with the results of another study of the radiative decay of J/ψ performed by DM2 at Orsay.¹⁰ The seeming disparity between the radiative decay and the hadronic production experiments makes this channel an especially interesting one for further study. Jetset will examine the disputed region very closely, with a mass resolution of just 1 MeV.

The Jetset detector is capable of making measurements in several different physics channels to complement $\phi\phi$. Areas currently under consideration include $K_S K_S$, $\bar{K}^* K^*$ and neutral channels such as $\pi^0 \pi^0$ and $\eta\eta$, as well as $\phi\phi\pi^0$ to allow the production of $\phi\phi$ with exotic quantum numbers.

EXPERIMENTAL METHOD

The Jetset detector is illustrated in Fig. 2. The hydrogen-cluster jet target, here shown with the source at the bottom of the picture and the sink at the top, intersects the antiproton beam at the center of the detector; the antiprotons' direction is from left to right.

Around a thin beam pipe lie 60 trigger scintillators, covering polar angles from 15 to 45 degrees (40 counters) and from 45 to 65 degrees (the remaining 20). They have full 2π azimuthal coverage. These are at the heart of the detector, since they, with the Cherenkov counters, provide the first-level trigger; they also provide a reference "time zero" for the charged-particle tracker.

Tracking is performed by more than 2000 straw drift tubes. Those in the barrel (designed to locate tracks with polar angles $> 45^\circ$) are in a honeycomb arrangement with the straws lying parallel to the beampipe, whereas the forward straws are arranged transversely in alternating horizontal (x) and vertical (y) layers. Drift time measurements reveal the radial distance of the track from the center of each hit straw with a resolution of $\sigma = 150 \mu\text{m}$, and charge division in the barrel segment gives the z coordinate of each hit with a longitudinal resolution of $\sigma = 8 \text{ mm}$.

Since the detector is nonmagnetic, momentum cannot be measured directly. It is therefore essential to have good β determination. This is provided, within 10-20% for particles of $\beta < 0.8$, by a silicon-pad dE/dx detector which lies downstream of the forward straws. A ring-imaging Cherenkov counter (RICH) is being developed for Jetset, to provide these measurements in the high- β region where the silicon is no longer sensitive.

The threshold Cherenkov counters are filled with either water (for low energy operation) or freon (for higher energies). These provide an essential rejection, at the first-level trigger, of fast pions which fulfill the multiplicity requirements in the beam pipe scintillators. In both the forward and barrel regions there are 24 counters, each covering an azimuthal angle of 15° .

After the Cherenkov counters, the kaons traverse a three-layer scintillator hodoscope. This is again divided into forward and barrel regions, covering polar

angles up to 45° and from 45° to 135° respectively. The hodoscope is formed from straight, left-bent and right-bent scintillators (spirals in the forward, helices in the barrel), a coincidence of which shows a "pixel" through which the particles have passed.

The outermost layer of the Jetset detector is an electromagnetic calorimeter consisting, in the forward region, of 300 blocks ("towers") of lead with an embedded matrix of scintillating fibres. The energy resolution of $\sigma/E = 6.3\%/\sqrt{E}$ (comparable to that of lead glass) allows efficient reconstruction of π^0 s and η s. In the barrel, the same lead/scintillating fiber mixture is used to detect, and veto, photons; an upgrade foreseen for the near future will provide good position resolution in the barrel region, thereby opening a window to the neutral physics channels mentioned above.

RESULTS AND ANALYSIS

Two short test runs, in December 1990 and April 1991, provided a small data sample from which to extract $\phi\phi$ events. Each ϕ may decay, with a branching ratio of 0.49, into a pair of charged kaons. We therefore require a multiplicity of four charged particles in our triggering "pipe" scintillators (a window which may be expanded to 3-5 if the rates are sufficiently low, to allow for some inefficiency or for the possibility of multiple hits). Since the kaons are relatively massive, compared with pions, they tend to have a lower velocity, so restricting to 1 (or 2 at high incident momenta) the number of threshold Cherenkov counters that we allow to fire effectively eliminates the large background of $\bar{p}p \rightarrow 4\pi$.

Offline, several harsh cuts were made in order to perform a quick search for four-kaon events; such cuts will, of course, be opened up considerably when a full analysis is carried out. These first cuts are as follows:

(i) All four charged particles were required to be in the forward region, i.e., exactly four of the 15-45 degree pipe scintillators had to have been hit and, in addition, no barrel "pixels" (from our scintillator hodoscope) were allowed.

(ii) The tracks in the forward straws had to be "clean." Here, a simple vertex-based trackfinding algorithm was used; pixels from the scintillator hodoscope were used to "seed" tracks, in order to make the first association between hit straws in the x- and y- layers. Events in which four tracks could not be reconstructed were rejected.

(iii) In order to ensure transverse momentum balance, we required that the azimuthal angle between adjacent hit pipe scintillators should be not more than 180° .

(iv) Events with photons in the barrel were rejected.

(v) The kinematic equations were then solved, assuming that the particles were indeed kaons. The resulting momenta had to match the pattern of Cherenkov counters that fired.

(vi) At an incident momentum of 2 GeV/c, the background reaction $\bar{p}p \rightarrow \bar{p}p\pi^+\pi^-$ becomes extremely intrusive. All four of the particles generated in these events are of low β , and therefore easily pass the first level Cherenkov counter trigger cuts; the kaons, unfortunately, have a relatively high β , making it necessary to relax the Cherenkov requirement to allow up to two counters to fire. Since, at the time of writing, the silicon detector is not yet fully calibrated, we lack the precise velocity

information that would allow us to distinguish this background from true 4K events. Monte Carlo studies, however, have shown that a requirement on the fitted tracks that all momenta be greater than $0.4 \text{ GeV}/c$ cuts out the background completely, although at the price of a substantial fraction of the real 4K events. This cut, which removes events fairly uniformly throughout the kaons' Goldhaber plot, was implemented at the higher energy only.

Fig. 3. Goldhaber plot of invariant masses of pairs of kaons.

The invariant masses of all combinations of pairs of kaons from events at $1.5 \text{ GeV}/c$ that passed the above cuts are shown in a Goldhaber plot (Fig. 3). At this incident momentum, 1.9 million events passed the first-level trigger, of which 71 survived the cuts; of these, 31 had at least one solution in which both pairs of kaons had an invariant mass in the range $1.00\text{-}1.04 \text{ GeV}/c^2$, and were thus consistent with $\phi\phi$ events. With our integrated luminosity over this data sample of $9 \times 10^{34} \text{ cm}^{-2}$, a net acceptance and efficiency within these cuts of approximately $1/4 \%$ (further studies are needed to confirm this number), and a branching ratio $\phi \rightarrow K^+ K^-$ of 0.49, we obtain a cross section for $\bar{p}p \rightarrow \phi\phi$ consistent with the range $0.2\text{-}2 \mu\text{b}$. Possibly of more interest is the ratio of 4K events consistent with $\phi\phi$ production to the total number of 4K events, which, at about 40%, is surprisingly large.

Since the additional momentum cut at 2 GeV/c diminished our event sample in a way that is not yet clearly understood, we cannot with any confidence make a similar cross section estimate from these higher energy data; suffice it to say that the $\phi\phi$ peak once again stands out clearly from the 4K background.

CONCLUSION

Analysis of two short test runs of the Jetset experiment at LEAR has revealed clear evidence of the reaction $\bar{p}p \rightarrow \phi\phi$. A preliminary estimate of the cross section for this process puts it in the range 0.2-2 μb . At a c.m. energy of 2.25 GeV/c, this reaction seems to constitute about 40% of the total cross section for $\bar{p}p \rightarrow 4K$. Strong evidence for $\phi\phi$ production has also been seen at a c.m. energy of 2.43 GeV.

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