Observation of an Enhancement in $\bar{p}p \to \pi^+\pi^-$ and $\bar{p}p \to K^+K^-$ Cross Sections at $\bar{p}$ Momentum of ~ 500 MeV/c

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The reactions $\bar{p}p \to \pi^+\pi^-$ and K^+K^- have been studied at 390, 490, 590, 690, and 780 MeV/c. An enhancement of about 150 μb has been observed in the cross sections of both reactions at the same beam momentum of 490 MeV/c. If this structure is interpreted as a meson resonance, it has a mass of 1940 ± 20 MeV and a width of less than 40 MeV.

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The search for resonances in the $\bar{p}p$ system has long been a subject of extensive experimental investigation because of their exotic nature. Indeed, if they exist, they are the best candidates for baryonia. However, the initial excitement brought about by the observations of several narrow peaks later faded, because these narrow peaks have not been confirmed in the subsequent experiments.[1] Yet, there remain candidates for broad $\bar{p}p$ resonances observed in $\bar{p}p$ total, elastic, and annihilation cross sections, namely, the T and U.[1] Below 1 GeV/c, no resonance structures have been found in the $\bar{p}p$ total cross section.[2,3] However, since the sensitivity of the total-cross-section measurement by Sumiyoshi *et al.*[2] for broad (width $\gtrsim 20$ MeV) resonances is about 1 mb, it is still an open question whether there exist resonances with peak cross sections of less than 1 mb.

Antiproton-proton annihilation into two pseudoscalar mesons has many advantages for resonance search even though the cross sections are small: (i) Signals are simple and clean; (ii) the quantum numbers of the final states are restricted; and (iii) partial-wave analyses can be performed, if polarization parameters are measured in addition to the differential cross sections. In spite of these attractive features, high-statistics data on the reactions $\bar{p}p \to \pi^+\pi^-$ and K^+K^- are available only for the momentum interval 0.79–2.43 GeV/c.[4] Below 0.79 GeV/c, a few experiments[5–8] provided integrated cross sections of these reactions. The angular distributions were also measured,[5,8] but their statistics are quite limited. No resonance candidate was reported from these measurements.

In this experiment, we have measured the differential cross sections of the reactions $\bar{p}p \to \pi^+\pi^-$ and K^+K^- at 390, 490, 590, 690, and 780 MeV/c using a counter technique with better statistical accuracy than the previous experiments. The measurement was performed with a low-momentum separated beam (K3) at the National Laboratory for High Energy Physics (KEK). In this experiment, we also measured $\bar{p}p$ elastic and charge-exchange differential cross sections.[9,10] A 17.5-cm-long liquid-hydrogen target was located at the center of a dipole magnet with a field of 2.5 kG. A description of the detectors and event trigger has been given in Refs. 9 and 10.

The absolute accuracy of the beam momentum estimated from the known properties of the K3 beam-channel magnets was ±0.5%. We checked independently that the beam momentum was correct to within ±2%, using the kinematical constraint of the $\bar{p}p \to \pi^+\pi^-$ and K^+K^- events. The momentum spread of the incident beam was ±2.5%. In order to reject pion contamination in the beam at the trigger level, cuts were applied on the recorded pulse-height and timing data of the trigger counters. The purity of the incident antiprotons after these cuts was better than 99% at all momenta.

For the analysis of $\bar{p}p \to \pi^+\pi^-$ and K^+K^-, we mainly used a cylindrical drift chamber (CDC), four planar drift chambers (DC1–DC4), forward and backward time-of-flight (TOF) counters, and scintillation counters attached to the magnet pole faces (the pole-face counters). For a rough selection of $\pi^+\pi^-$ and K^+K^- events from the huge background of the annihilation events, the following requirements were imposed on the data: (i) no pole-face counter hit, (ii) the presence of two outgoing charged tracks in the CDC and DC's, and (iii) coplanarity.

Figure 1(a) shows the coplanarity distribution at 590 MeV/c, where the variable θ_c is defined as the angle between one outgoing track and the vector product of the incident-beam track and the other outgoing track. A clear peak centered at 90° corresponding to the

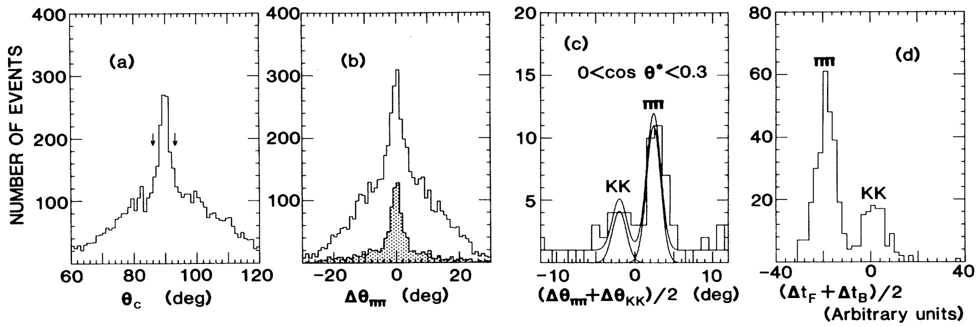

FIG. 1. (a) Coplanarity distribution. (b) The unshaded histogram shows the $\Delta\theta_{\pi\pi}$ distribution before the coplanarity cut, while the shaded one shows the same after the cut. (c) The $(\Delta\theta_{\pi\pi}+\Delta\theta_{KK})/2$ distribution after the coplanarity cut for the interval $0<\cos\theta^*<0.3$. The curves show the result of a fit described in the text. (d) The $(\Delta t_F+\Delta t_B)/2$ distribution for the events with $|\cos\theta^*|>0.9$. All the distributions shown in (a)–(d) were obtained at 590 MeV/c.

dimeson events is observed. The unshaded histogram in Fig. 1(b) shows the $\Delta\theta_{\pi\pi}$ distribution where $\Delta\theta_{\pi\pi}$ is defined as follows. For one of the measured angles of the outgoing particles, the angle of the other can be predicted if the kinematics of $\bar{p}p\to\pi^+\pi^-$ or $\bar{p}p\to K^+K^-$ is assumed. We then obtain the difference between the predicted and measured angles $\Delta\theta_{\pi\pi}$ for $\bar{p}p\to\pi^+\pi^-$ and $\Delta\theta_{KK}$ for $\bar{p}p\to K^+K^-$. In this figure, the K^+K^- peak is buried in the $\pi^+\pi^-$ peak, because $|\Delta\theta_{\pi\pi}-\Delta\theta_{KK}|$ depends on the meson production angle on which no restriction is yet imposed. The shaded histogram in Fig. 1(b) shows the $\Delta\theta_{\pi\pi}$ distribution after the coplanarity cut shown by the arrows in Fig. 1(a). In order to suppress the background, the coplanarity cut was tightly applied. Its efficiency was estimated to be $(79\pm4)\%$ by inspection of the peak in the $\Delta\theta_{\pi\pi}$ distribution of the events eliminated by this cut.

In order to separate the $\pi^+\pi^-$ and K^+K^- events, we used the opening angles in the angular region of $|\cos\theta^*|<0.9$, where θ^* is defined as the angle between the incident antiproton and the negative outgoing particle in the center-of-mass frame. For this purpose, this angular region was divided into sufficiently narrow subregions and a distribution of $(\Delta\theta_{\pi\pi}+\Delta\theta_{KK})/2$ was plotted for each subregion. As an example, Fig. 1(c) shows this distribution for $0<\cos\theta^*<0.3$ at 590 MeV/c. Two peaks corresponding to $\pi^+\pi^-$ and K^+K^- events are observed. To deduce the numbers of the $\pi^+\pi^-$ and K^+K^- events, this distribution was fitted with two Gaussians and a constant background term. The widths of the Gaussians were constrained by the angular resolution (1.2° rms), and the distance between the two peaks was constrained by the two-body kinematics.

Since the difference between the $\pi^+\pi^-$ and K^+K^- opening angles becomes small in the forward and backward directions, we relied on the TOF counters for the identification of the $\pi^+\pi^-$ and K^+K^- events for $|\cos\theta^*|>0.9$. It was required that both forward and backward TOF counters had hits, and the differences between the measured TOF's and the TOF's predicted for the hypothesis $\bar{p}p\to K^+K^-$, Δt_F and Δt_B, were obtained. The subscripts F and B refer to the forward and backward TOF counters, respectively. The distribution of $(\Delta t_F+\Delta t_B)/2$ then should exhibit clusters of $\pi^+\pi^-$ and K^+K^- events separated by about four standard deviations at all momenta. Figure 1(d) shows an example of this distribution. The numbers of the $\pi^+\pi^-$ and K^+K^- events were determined on the basis of the $(\Delta t_F+\Delta t_B)/2$ distribution. Actually, the TOF counters covered a somewhat wider angular region, $|\cos\theta^*|\gtrsim0.85$, and the consistency of the two methods of identifying $\pi^+\pi^-$ and K^+K^- events was checked to be satisfactory in the region $0.85\lesssim|\cos\theta^*|\lesssim0.95$.

The total uncorrected numbers of the $\pi^+\pi^-$ and K^+K^- events obtained were about 3400 and 1000, respectively. To deduce the differential cross sections, a Monte Carlo program was written to calculate the combined correction factors due to the detector acceptance, decay correction, and reconstruction efficiency. The differential cross sections obtained are shown in Fig. 2(a) for $\bar{p}p\to\pi^+\pi^-$ and in Fig. 2(b) for $\bar{p}p\to K^+K^-$. The error bars indicated are statistical only. The total systematic error is estimated to be $\pm8\%$. The curves in these figures show the fitted results with a Legendre polynomial series of up to sixth order. A full description of the differential cross sections and the Legendre-expansion results is given elsewhere.[11] In Fig. 2, our results at 780 MeV/c are compared with the data reported by Eisenhandler *et al.*[4] at 790 MeV/c. Here, the absolute values of the $\bar{p}p\to\pi^+\pi^-$ data of Eisenhandler *et al.* are normalized to our data, because their $\bar{p}p\to\pi^+\pi^-$ cross section is larger than ours by about 30% [see Fig. 3(a)]. Apart from this, the results of both experiments seem to agree well.

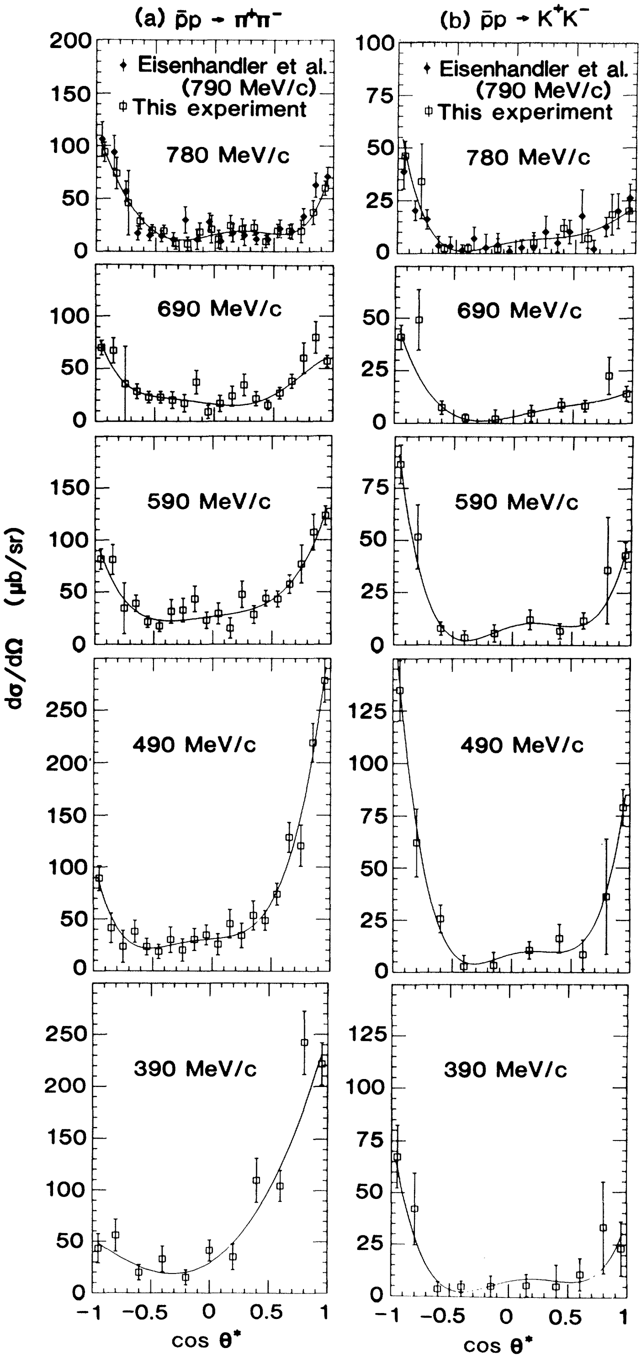

FIG. 2. Differential cross sections of the reactions (a) $\bar{p}p \to \pi^+\pi^-$ and (b) $\bar{p}p \to K^+K^-$. For comparison, the data of Eisenhandler *et al.* (Ref. 4) at 790 MeV/c are also shown (for $\bar{p}p \to \pi^+\pi^-$, only part of the data appear). The curves show the results of Legendre-expansion fits to our data.

The cross sections $\sigma(\pi^+\pi^-)$ and $\sigma(K^+K^-)$ are given by $4\pi a_0$, and a_0 is the fitted expansion coefficient of the zeroth-order Legendre polynomial. Figures 3(a) and 3(b) show $\sigma(\pi^+\pi^-)$ and $\sigma(K^+K^-)$,

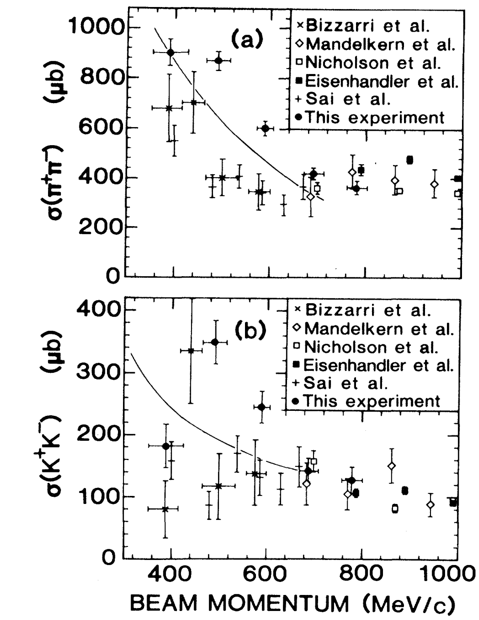

FIG. 3. Cross sections (a) $\sigma(\pi^+\pi^-)$ and (b) $\sigma(K^+K^-)$. The theoretical curves are normalized to our $\sigma(\pi^+\pi^-)$ data at 390 MeV/c.

respectively, together with previous data.[4-8] At two highest momenta, our data are statistically consistent with the other data,[4,6-8] but at 490 and 590 MeV/c, our data are higher than the data of two previous experiments[5,8]: $\sigma(\pi^+\pi^-)$ shows a small bump,[12] and $\sigma(K^+K^-)$ shows a clear peak, around 590 MeV/c. However, we note that the data of Bizzarri *et al.*[5] show similar structures in both $\sigma(\pi^+\pi^-)$ and $\sigma(K^+K^-)$ at a lower momentum (~ 440 MeV/c), although their statistical significances are much lower than ours. It should be noted at this point that in the s-channel $\bar{p}p$ experiment, there is no well-established peak usable for self-calibration of the energy scale, and this makes the momentum calibration of the low-energy $\bar{p}$ beam difficult. The results of Bizzarri *et al.*[5] agree better with our results if an $\sim 10\%$ upward shift of the momentum scale is admitted for their data.

The curves in Fig. 3 are taken from the recent calculation[13] using a nonrelativistic quark model, which are normalized rather arbitrarily to our $\sigma(\pi^+\pi^-)$ data at 390 MeV/c. If these curves are assumed to represent the nonresonant background, the observed enhancements are about 150 μb for both $\bar{p}p \to \pi^+\pi^-$ and $\bar{p}p \to K^+K^-$. On this assumption, the statistical significances of these enhancements are about four standard deviations. Although it is premature to draw a definite conclusion from the present results alone, it is tempting to interpret the observed structure as due to a new meson resonance. We estimate the mass of this resonance to be 1940 ± 20 MeV from the peak position. The width estimated from the data is less than

40 MeV. The width cannot be very narrow. Otherwise, the resonance cross section would be very large. No such structure has been observed in $\bar{p}p$ total cross section.[2,3] However, the width is too narrow for this resonance to be an ordinary meson, unless a certain suppression mechanism is at work.

The mass of this state coincides with that of the S resonance, which was a candidate for a baryonium but has not been confirmed in recent $\bar{p}p$ total-cross-section measurements.[1–3] From the results of Sumiyoshi *et al.*,[2] an upper limit for resonance cross sections in the $\bar{p}p$ total cross section is about 1 mb for a width of 10–40 MeV. A simple Breit-Wigner formula then gives $\Gamma_{\bar{p}p}/\Gamma \lesssim 0.046/(2J+1)$, where $\Gamma_{\bar{p}p}$ is the elastic width, Γ the total width, and J the angular momentum.[14] This indicates that the coupling of this resonance to the $\bar{p}p$ channel is smaller than the coupling to the $\pi^+\pi^-$ and K^+K^- channels, because $\Gamma_{\pi\pi}/\Gamma \sim \Gamma_{KK}/\Gamma \gtrsim 0.15$, where $\Gamma_{\pi\pi}$ and Γ_{KK} are the partial widths to the $\pi^+\pi^-$ and K^+K^- channels. It seems unlikely, therefore, that this resonance is a baryonium which is considered to couple strongly to the baryon-antibaryon channel. The observed nearly equal branching ratios to the $\pi^+\pi^-$ and K^+K^- channels may suggest either that this resonance has a large $s\bar{s}$ component or that it is a gluonic state such as a glue ball or a hybrid meson, since the gluon is "flavor blind." In any case, further study of this structure is urgently needed.

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[12]Preliminary results of this experiment have been reported by Nakamura and Tanimori (Ref. 9), where the observation of an enhancement was claimed only for $\sigma(K^+K^-)$. Later, the last 30% of the data at 490 MeV/c were found to exhibit a shift of the TOF start timing, which caused a loss of both $\pi^+\pi^-$ and K^+K^- events. However, part of the lost $\pi^+\pi^-$ events contaminated the K^+K^- events. Consequently, after correction for this error, $\sigma(\pi^+\pi^-)$ was enhanced compared to the preliminary results.

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