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Evidence for New 0^- S Resonances in the $\pi^+\pi^-\pi^-$ Systems

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Partial-wave analysis has been performed on 120 000 $\pi^-\pi^-\pi^+$ events coherently produced on nuclear targets in a π^- beam of 40 GeV/c. Evidence has been found for a 0^- S resonance at 1.24 GeV with a width $\Gamma \approx 0.36$ GeV. The data also suggest the presence of another 0^- S resonance of similar width near 1.8 GeV. These observations can be interpreted as radial excitations of the π meson.

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The existence of resonant $I^GJ^PL = 1^-0^-$ S states is expected in the frame of the quark model as radial excitations of the pion. An indication that a 0^- S resonance might exist has been put forward in the data of Daum *et al.*,[1] where the mass distribution of the 0^- S wave peaks at ~ 1.2 GeV. Two recent observations of a 0^- S resonance are in disagreement: Whereas our partial-wave analysis[2] (PWA) of events coherently produced on nuclear targets shows a resonance at ~ 1.2 GeV ($\Gamma \approx 0.33$ GeV), further results obtained from data on proton targets[3] suggest the existence of a 0^- S resonance at 1.34 GeV with $\Gamma \approx 0.23$ GeV. In this Letter we show new results concerning the 0^- S and 1^+ S resonances in the A_1 region and we extend the analysis up to $M_{3\pi} = 2.0$ GeV.

The data have been obtained in the 40-GeV/c π^- beam of the Serpukhov accelerator using nine different nuclear targets (Be, C, Al, Si, Ti, Cu, Ag, Ta, and Pb). The experimental setup is described elsewhere.[4] We use for the PWA a total sample of ~ 120 000 $\pi^-\pi^-\pi^+$ events. The acceptance of the apparatus decreases smoothly from ~ 100% at $M_{3\pi} \simeq 0.9$ GeV to ~80% at $M_{3\pi} \simeq 2.0$ GeV.

The results presented in this Letter concern only "coherent" samples of events with $t' \leq t'^*$, where t'^* corresponds to the first diffractive minimum of the differential cross sections for the different nuclear targets[4] [e.g., $t'^* \approx 0.04$ (GeV/c)^2 for Be and $t'^* \approx 0.008$ (GeV/c)^2 for Pb]. Because of the steepness of the t' slopes for the coherent interactions on nuclear targets [e.g., $B \sim 50$ (GeV/c)$^{-2}$ for Be and $B \sim 300$ (GeV/c)$^{-2}$ for Pb], about $\frac{3}{4}$ of the events are included in the coherent samples and the incoherent background is very small (~ 12% for Be and ~ 1.5% for Pb).

We have used for the partial-wave analysis the PWA program of the Illinois group.[5] The analysis of the "coherent" events is in principle easier than that of the proton data: There is no need for N^* cuts; all spin-flip amplitudes are suppressed; the phase measurements are reliable because of the maximal interference between waves. Nevertheless, there remains an unavoidable difficulty inherent in the PWA method: A direct decay into three free pions cannot be treated with PWA program and the 3π system is assumed to decay into an intermediate di-pion and a pion. Whereas the 1^- (ρ) and 2^+ (f) decay di-pions are good resonances, there is a problem how to describe the di-pion 0^+: Neither the parametrization with an "ϵ" resonance nor that that with elastic ($\pi\pi$) phase shifts is actually corresponding to the reality. We have used in our analysis three descriptions of the 0^+ di-pion: the "ϵ" resonance ($M_R = 0.77$ GeV, $\Gamma = 0.40$ GeV), the elastic $\pi^+\pi^-$ phase shifts,[6] and the recently published $\pi^0\pi^0$ phase shifts.[7]

In general we have considered a wave as negligible when its intensity was equal to zero within errors or smaller than 1%. These criteria eliminated all spin-flip amplitudes (including the $2^+ D$ and the $1^- P$ waves)[4] in our coherent sample; this simplification compared to previous similar data[8] on nuclear targets at 15 GeV/c is entirely due to higher beam momentum in the present experiment. In the A_3 region where the coherence factor K between waves is often smaller than $K \sim 0.5$, we have neglected even amplitudes a little stronger than 1% if their presence did not affect significantly the relative phases of the main waves. In this way our set of necessary waves in the region $M_{3\pi} < 1.1$ GeV is reduced to the following amplitudes: $0^- S$, $0^- P$, $1^+ S$, $1^+ P$, and $2^- P$; above $M_{3\pi} = 1.1$ GeV we have to add the $1^+ D$ and $2^- S$ waves.

In Fig. 1 we show the mass spectra of $0^- S$, $0^- P$, and $1^+ S$ partial waves using all these above mentioned parametrizations of the 0^+ di-pion. The "coherent" events of all targets have been put together. It is seen that whereas the mass distribution of the $0^- S$ is not very sensitive to the description of its decay di-pion, the $1^+ S$ mass

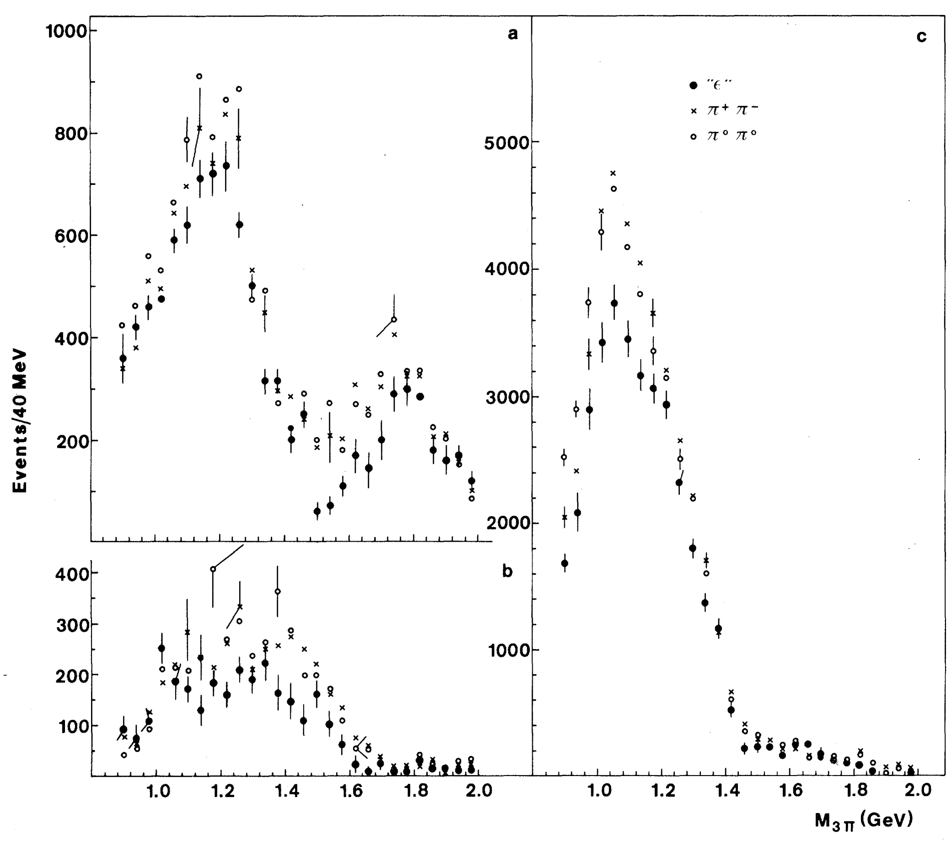

FIG. 1. Mass dependence of (a) $0^- S$, (b) $0^- P$, and (c) $1^+ S$. Filled circles, crosses, and open circles correspond to different parametrizations of the 0^+ di-pion: "ϵ" resonance, phase shifts of Ref. 6, and phase shifts of Ref. 7, respectively.

shapes are strongly influenced. This is due to the $1^+ SP$ interference term: the number of events assigned to this term, when the 0^+ is described as a resonance, is large and negative in the threshold region and large and positive above $M_{3\pi} \sim 1.0$ GeV, whereas for the elastic $\pi\pi$ phase shifts it is everywhere small and negative. Since the "true" description of the 0^+ is not known, one has to argue very carefully about the shape of the $1^+ S$ mass distribution. The $0^- S$ mass spectrum exhibits two peaks, one near 1.2 GeV and another one near 1.8 GeV, the "valley" between the two peaks is better seen using the "ϵ" description of the 0^+ than in the two phase-shift parametrizations.

The $2^- P$ wave behaves in the A_1 region (especially in $M_{3\pi} \leq 1.2$ GeV) as a rather incoherent wave: It tends to vanish in forward direction and keeps even there a relatively strong spin-flip component; its coherent factors are rather low. Therefore this amplitude cannot be used as a reference wave for the measurement of relative phases in the A_1 region.

In Fig. 2(a) we plot the coherence factor K between $0^- S$ and $1^+ S$ waves. It decreases smoothly with increasing $M_{3\pi}$ except for an abrupt drop around $M_{3\pi} = 1.5$ GeV corresponding to the "valley" between the two $0^- S$ peaks. In general the degree of coherence is the highest for the resonance description of the 0^+ di-pion. Indeed also the values of the likelihood function are systematically higher for this parametrization than for the $\pi\pi$ phase-shift descriptions of 0^+.

We show in Fig. 2(b) that the $0^- S$–$1^+ S$ relative phase is nearly constant across the A_1 region. It clearly means that if the $1^+ S$ wave is a resonance then also the $0^- S$ amplitude should be a resonance with similar parameters.

In Fig. 3 we plot the phases of the $0^- S$ and $1^+ S$ amplitudes relative to the $0^- P$ phase. The observed phase variation is in both cases the largest for the resonance parametrization of the 0^+ di-pion and amounts to $\sim 80°$ for the $0^- S$ wave and to $\sim 100°$ for the $1^+ S$ amplitude. We have to mention that an ambiguous "II" solution as discussed by Pernegr[8] appears in these data only very near the threshold ($M_{3\pi} \lesssim 1.0$ GeV); therefore we do not consider it as an actual competing solution.

A fit of a Breit-Wigner resonance and a second-order polynomial background to the intensity of the $0^- S$ wave in the A_1 region gives $M_R \simeq 1.24 \pm 0.03$ GeV with $\Gamma \simeq 0.36 \pm 0.12$ GeV. The mass values obtained by fitting both the mass distributions and the phases are the same within errors as that quoted above.

The phase of the reference wave $0^- P$ is very likely not intrinsically constant: In the $M_{3\pi}$ interval between 1.2 and 1.4 GeV, where it is measurable against the $2^- P$ phase, it increases for at least 30° and it continues to rise for about the same amount between 1.4 and 1.6 GeV relative to the $1^+ S$. The "true" phase motions of the $0^- S$

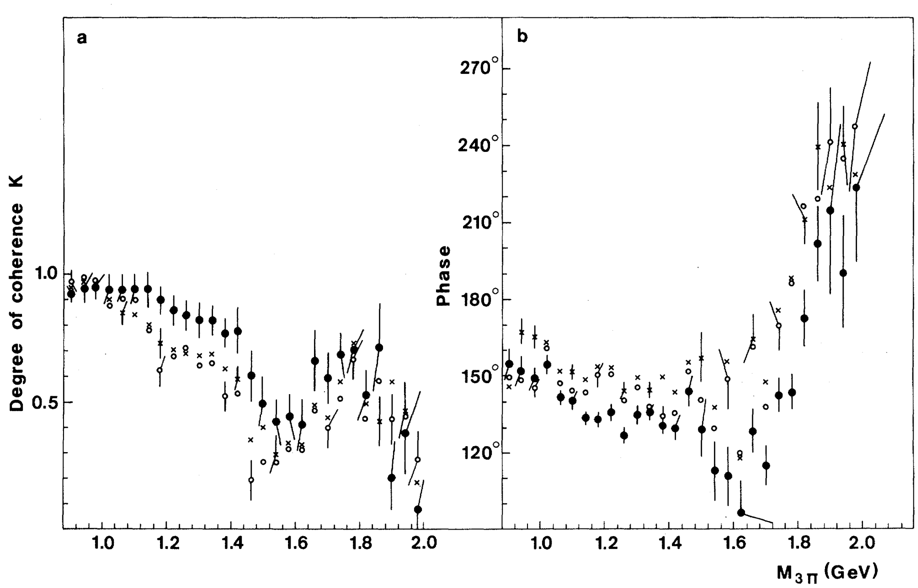

FIG. 2. (a) Coherence factor K between $0^- S$ and $1^+ S$ waves. (b) Relative phase between $0^- S$ and $1^+ S$ waves. Symbols as in Fig. 1.

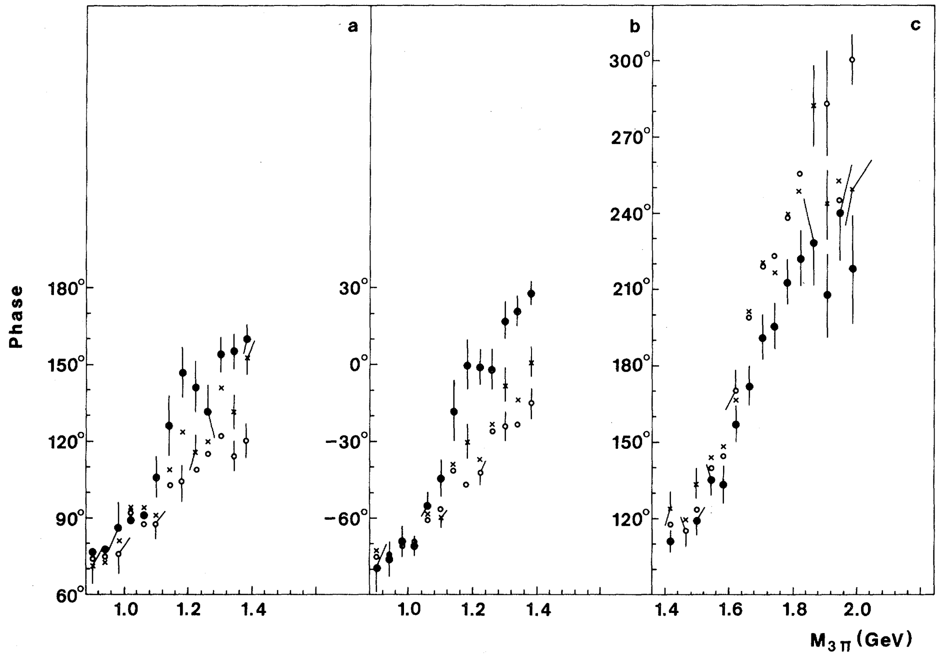

FIG. 3. Relative phase between (a) 0^- S and 0^- P, (b) 1^+ $S-0^-$ P, and (c) 2^- $S-1^+$ S waves. Symbols as in Fig. 1.

and 1^+ S waves are therefore larger than the relative variations shown in Fig. 3.

Since the signal of 0^- P becomes negligible above $M_{3\pi} \sim 1.6$ GeV, we have chosen the 1^+S as reference wave in the region of the second 0^- S enhancement. We show in Fig. 3(c) that the established resonance behavior of the 2^- S wave is well reproduced using the 1^+S phase as a reference. Therefore, we believe that the rapid variation of the 0^-S–1^+ S relative phase across the region of the second 0^- S mass peak in Fig. 2(b) is not accidental in spite of large errors. We rather believe that it can be interpreted in terms of a second 0^- S resonance.

Its mass, obtained by a fit of a Breit-Wigner resonance and a second-order polynomial background on the 0^- S signal, is $\sim 1.77 \pm 0.03$ GeV with $\Gamma \approx 0.31 \pm 0.05$ GeV for all three parametrizations of the 0^+ di-pion; the same value is found by fitting together the mass distributions and the relative phases.

In conclusion, we have brought evidence of a $I^GJ^PL = 1^-$ 0^- S state of mass $\simeq 1.24 \pm 0.03$ GeV and width $\sim 0.36 \pm 0.12$ GeV, which is in good agreement with recent predictions of the first radial excitation of the pion (π').[9] We believe that the difference in the position and in the width of this resonance compared to the results of Bonesini *et al.*[3] can be explained by the strong suppression of the incoherent background and by a nearly 100% acceptance in our data.

We observe another $I^GJ^PL = 1^-$ 0^- S resonance at 1.77 ± 0.03 GeV ($\Gamma \simeq 0.31 \pm 0.05$ GeV) which could correspond to a second radial excitation of the pion (π''). This evidence is clear, even if in this higher $M_{3\pi}$ region the statistics is smaller and the analysis is more complex than in the region of the π'.

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