Observation of an excited state of a pion: a new pseudoscalar meson

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A new pseudoscalar meson has been discovered by a partial-wave analysis of a $\pi^+\pi^-\pi^-$ system produced during the diffractive dissociation of π mesons with a momentum of 40 GeV/c by nuclei. This new pseudoscalar meson has a mass of 1.205 ± 0.007 GeV/c^2, a width of 0.320 ± 0.035 GeV/c^2, and quantum numbers $I^G J^P = 1^- 0^-$. In a quark-structure interpretation, this new particle is a radial excitation of a pion.

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In this letter we are reporting the results of a partial-wave analysis of a 3π system produced during the diffractive dissociation of π mesons with a momentum of 40 GeV/c by nuclei,

$$\pi^- + \mathcal{Z} \to \pi^+ + \pi^- + \pi^- + \mathcal{Z},$$

in the region of the $A1$ resonance at a low 4-momentum transfer.

The data used for the analysis were obtained in a joint experiment, using the MIS spectrometer of the Joint Institute for Nuclear Research,[1] carried out in a beam of negative π mesons with a momentum of 40 GeV/c on the accelerator of the Institute of High-Energy Physics at Serpukhov. The total statistical base of 3π events with the nine nuclei Be, C, Al, Si, Ti, Cu, Ag, Ta, and Pb was 110 000 events. Of these events, 75% satisfied the criterion for the coherent production of 3π systems with $t' < t'^*$, where t'^* corresponds to the first minimum in the differential cross section [for the lead nucleus, $t'^* = 0.008$ (GeV/c)^2, because of the large inclination of the diffraction cone, –360 (GeV/c)$^{-2}$].

In the diffractive production of particles, the nucleus remains in the ground state, and at low transfer levels the system of particles produced retains all the quantum numbers of the incident particle; the changes in the spin and parity correspond to "natural" exchange. These reactions therefore present an important opportunity to unambiguously analyze the spin and parity of the product systems and to study the resonance production in the region of the $A1$ resonance. Because of the large energy transfer to the product system (~1 GeV) at a low 4-momentum transfer [~0.01 (GeV/c^2)], a study of these processes makes it possible to study the excited states of dynamic structures of diffractively produced systems.

Nuclear targets have several advantages over proton targets for experiments on diffraction: a) Because of the small 4-momentum transfer, spin-flip amplitudes are negligible. b) The minor contribution of incoherent processes and the high degree of wave coherence permit reliable measurements of the relative phase shifts. c) The analysis is not complicated by ambiguities resulting from the production of an N^* resonance.

The partial-wave analysis of the 3π events was carried out by the program developed at the University of Illinois,[2] modified to reflect the geometric acceptance of the trigger system of the magnetic spectrometer. The angles at which the mesons were emitted from the target, the momentum transfer, and the invariant masses of the three-pion system had to be measured highly accurately for a determination of the contributions of the various waves from the angular distributions of the mesons. In the MIS spectrometer, the angular accuracy was 0.45 mrad, and the accuracy in terms of the momentum transfer was 17 MeV/c, so that a momentum transfer as low as 3×10^{-4} (GeV/c)^2 could be measured. The resolution in terms of the mass of the three-meson system was 26 MeV/c^2 for $m_{3\pi} = 1.1$ GeV/c^2 and 34 MeV/c^2 for $m_{3\pi} = 1.7$ GeV/c^2.

The data analysis system excluded 8% of the events, 6% because of short tracks and 2% because of track overlap. An analysis showed that this loss of events did not affect the angular characteristics of the mesons. The partial-wave-analysis program also incorporated the possible loss of events of a particular spatial topology because of the finite geometric acceptance of the spectrometer for the real and imaginary parts of the amplitude of the process. This correction varied slowly, from 100% to 96% from bin to bin along the mass scale for the 3π system. The following waves were incorporated in the analysis: $0^-S0+(\epsilon\pi)$, $0^-P0+(\rho\pi)$, $1^+S0+(\rho\pi)$, $1^+P0+(\epsilon\pi)$, $2^-P0+(\rho\pi)$, $2^-P1+(\rho\pi)$, $2^+D1+(\rho\pi)$, $2^-S0+(f\pi)$, $2^-D0+(\epsilon\pi)$. In the notation $JPLM\eta$ adopted for the meson system, L is the orbital angular momentum of the meson with respect to the dipion, M is the magnetic quantum number, and η is the sign of the reflection in the production plane. The waves of the unnatural series with spin flip were found to be of negligible importance in the coherent region, except for the 2^-P wave, for which the intensity contribution was 30%. The contribution of waves with $\eta = -1$ was exceptionally small, less than 0.1%; the waves of the natural series were found to make an extremely small contribution. The S state of the dipion system was parametrized both with an ϵ resonance and with the phase shift for elastic $\pi\pi$ scattering. The different parametrizations affected the intensity of the interference between the 1^+S and 1^+P waves, but they did not affect the 0^-S and 0^-P waves, for which the interference is very weak. In this letter we are reporting the results with the ϵ parametrization, which yields a systematically higher value of the maximum-likelihood function. As the reference wave we selected the 0^-P wave, since its signal varies slowly over the entire mass spectrum and also since the fundamental wave of the well-established $A2$ resonance 2^+D1^+ with respect to the 0^-P wave exhibits the resonance behavior characteristic of the $A2$ resonance.

Figures 1a and 1b show the intensities of the 1^+S and 0^-S waves for all the targets, analyzed together; Fig. 2 shows the behavior of the 1^+S–0^-P and 0^-S–0^-P relative phase shifts. The phase shift for the 1^+S wave is 110°, and that for the 0^-S wave is 85°. The phase shift of the 1^+S wave remains essentially constant with respect to that of the 0^-S wave in the region $A1$ (Fig. 1c) and shows that both of the waves are

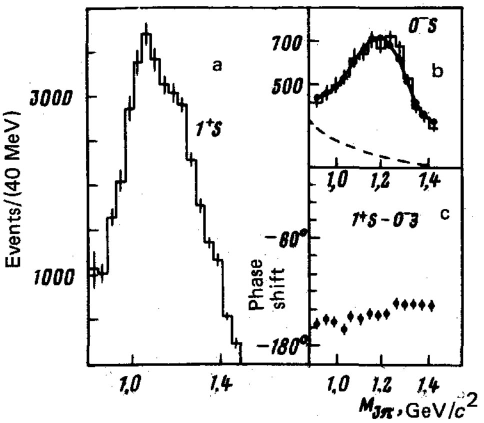

FIG. 1. a–Intensity of the 1^+S wave; b–intensity of the 0^-S wave (the solid curve shows the results of a fit by the Breit-Wigner resonance formula, while the dashed curve shows the nonresonant background); c–phase shift of the 1^+S wave with respect to the 0^-S wave.

resonance waves. The 0^-S mass spectrum does not depend on the parametrization of the dipion phase shift. A fit of the 0^-S mass spectrum by the relativistic Breit-Wigner formula with a slowly varying exponential background yields a mass $m = 1.20 \pm 0.007$ GeV/c^2 and a width $\Gamma = 0.320 \pm 0.035$ GeV/c^2. The 0^-S–0^-P relative phase shift of 85° in the $A1$ region, the Breit-Wigner shape of the mass spectrum, and the constancy of the 1^+S–0^-S relative phase shift therefore constitute direct evidence that a resonance is being observed in the $\pi^+\pi^-\pi^-$ system. This resonance has the quantum numbers of a pion which has reverted to the ground state of a pion through the emission of an ϵ meson.

This resonance can be explained in the quark model by identifying it with the excited state of the $q\bar{q}$ system (π').

In Refs. 3 and 4, the 1^+S phase shift was observed to remain relatively constant with respect to the 0^-S phase shift in the region of the $A1$ resonance. The authors of those papers concluded only that a 0^- resonance was possible, and they did not find direct proof of its resonance properties. The change in the 0^-S phase observed by them was only 40°.

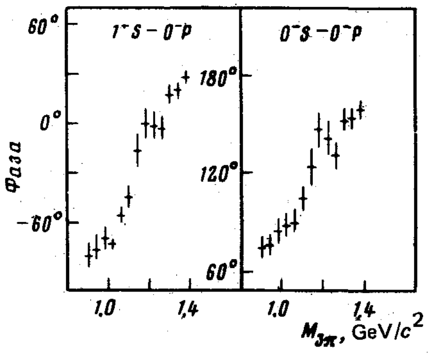

FIG. 2. Phase shift of the 1^+S wave with respect to the 0^-P wave and that of the 0^-S wave with respect to the 0^-P wave.

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