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Observation of a new narrow axial-vector meson $a_1(1420)$

The COMPASS Collaboration

Abstract

The COMPASS collaboration at CERN has measured diffractive dissociation of 190 GeV/c pions into the $\pi^-\pi^-\pi^+$ final state using a stationary hydrogen target. A partial-wave analysis (PWA) was performed in bins of 3π mass and four-momentum transfer using the isobar model and the so far largest PWA model consisting of 88 waves. A narrow $J^{PC} = 1^{++}$ signal is observed in the $f_0(980)\,\pi$ channel. We present a resonance-model study of a subset of the spin-density matrix selecting 3π states with $J^{PC} = 2^{++}$ and 4^{++} decaying into $\rho(770)\,\pi$ and with $J^{PC} = 1^{++}$ decaying into $f_0(980)\,\pi$. We identify a new a_1 meson with mass $(1414^{+15}_{-13})\,\mathrm{MeV}/c^2$ and width $(153^{+8}_{-23})\,\mathrm{MeV}/c^2$. Within the final states investigated in our analysis, we observe the new $a_1(1420)$ decaying only into $f_0(980)\,\pi$, suggesting its exotic nature. To our knowledge, such a state has never been predicted.

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The known light-meson spectrum is presently interpreted in terms of $q\overline{q}$ quark-model states that are associated with flavor SU(3) multiplets according to their mass and J^{PC} quantum numbers. For some J^{PC} combinations, more states were reported than can be accommodated by SU(3) symmetry. Depending on their coupling to specific production mechanisms and their decay pattern, these states are interpreted as either carrying a strong glueball component, e.g. $f_0(1500)$, as molecular-type excitations, e.g. $f_1(1420)$, or as tetra-quark states. For a detailed review see Ref. [1]. However, their exotic structure is under debate, unlike for states that carry spin-exotic quantum numbers, e.g. $J^{PC} = 1^{-+}$, and hence cannot be $q\overline{q}$ states. This is in contrast to the sector of heavy mesons containing c or b quarks, where exotic mesons have clearly been identified, e.g. X, Y, and Z states. In particular, the recent observation of charged Z-states, such as $Z_c(3900)^{\pm}$ and $Z_b(10\,610)^{\pm}$, has proven the existence of mesons with exotic structure [2, 3, 4].

In the sector of light mesons, the situation remains unresolved. The lowest-mass state discussed in this context is the $f_0(980)$, which contains $n\overline{n}$ ($n = \{u,d\}$) and a dominant $s\overline{s}$ component. It has also been interpreted as a $K\overline{K}$ molecule [5, 6, 7]. The $f_1(1420)$ with a width of only $55\,\mathrm{MeV}/c^2$ couples strongly to $K\overline{K}^*$ and was also suggested as molecular-type structure [8]. In Ref. [9], the Particle Data Group has tentatively adopted the scenario of $f_1(1420)$ being the SU(3) partner of $f_1(1285)$. In the class of spin-exotic mesons, the $\pi_1(1600)$ is the only meson observed by several experiments in different decay modes. However, the masses quoted and in particular the widths vary considerably between different experiments, and values for the width often exceed $400\,\mathrm{MeV}/c^2$. This suggests dynamical effects to be at work, similar to the case of $a_1(1260)$. The situation is characterized by individual states without recognizable pattern and, except for $a_0(980)$ and $f_0(980)$, the absence of any observed isospin partners.

In order to search for new exotic mesons, we have studied the diffractive reaction $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\mathrm{recoil}}$ with focus on waves with quark-model J^{PC} combinations [1]. We have studied the $J^{PC} = 1^{++}$ states in order to search for a possible partner of the isosinglet $f_1(1420)$. Our analysis aims at the charged isospin $I = 1$ analogue decaying into $\pi^-\pi^-\pi^+$. Although this final state and the mass range of 1 to $2\,\mathrm{GeV}/c^2$ have already been studied by many experiments, improvement by almost two orders of magnitude in sample size has opened a new avenue for analysis.

The COMPASS experiment [10, 11] is located at the M2 beam line of the CERN Super Proton Synchrotron. For this measurement, negative hadrons of $190\,\mathrm{GeV}/c$ were used impinging on a 40 cm long liquid-hydrogen target that was surrounded by a recoil-proton detector (RPD). The hadronic components of the secondary hadron beam at the target position are 96.8 % π^-, 2.4 % K^-, and 0.8 % $\overline{p}$. Pions are identified with a Cherenkov counter placed in the beam line at the entrance to the experimental area. The large-acceptance high-precision spectrometer is well suited for investigating high-energy reactions at low to intermediate values of the reduced squared four-momentum transfer t' to the target proton, where $t' \equiv |t| - |t|_{\mathrm{min}}$. For this measurement t' is chosen to be in the range of 0.1 to 1.0 $(\mathrm{GeV}/c)^2$. Outgoing charged particles are detected by the tracking system and their momenta are determined using two large-aperture magnets.

The data presented in this Letter were recorded in the year 2008. A detailed description of setup, data selection, and analysis scheme can be found in Refs. [12, 13]. The trigger is based on a recoil-proton signal in the RPD in coincidence with an incoming beam particle and no signal in the beam-veto counters. We require a production vertex located within the target volume, with one incoming beam-pion track and three outgoing charged particles, compatible with the pion hypothesis based on information from the RICH counter. The momentum sum of the outgoing particles is required to be equal to the average beam momentum within $\pm 3.78\,\mathrm{GeV}/c$. We require Feynman-x of the fastest final-state pion to be below 0.9 for rapidity differences between the fast π^- and the slower $\pi^-\pi^+$ pair in the range 2.7 to 4.5. This suppresses the small contamination of centrally produced final states, which contribute mainly at higher 3π masses. A total of 46×10^6 events was selected in the mass range between 0.5 to $2.5\,\mathrm{GeV}/c^2$.

[1] The C-parity refers to the neutral state of the isospin multiplet.

In order to extract the spectrum of resonances produced in the reaction, we have performed a partial-wave analysis (PWA) that is pursued in two steps. First, we fit the intensity distributions in the 5-dimensional phase space independently in one hundred $20\,\text{MeV}/c^2$ wide bins of 3π mass $m_{3\pi}$, each divided into 11 bins of t'. We adopt the notation $J^{PC}\,M^{\varepsilon}\,[\text{isobar}]\,\pi L$ to define partial waves. Here, ε denotes the reflectivity and $M \geq 0$ the magnitude of the spin projection along the beam axis (see Ref. [14]). L is the orbital angular momentum between the isobar and the bachelor pion in the decay of the 3π state. We use the isobar model, which for our fits contains 88 waves, namely 80 waves with positive reflectivity, 7 with negative and one non-interfering wave representing uncorrelated three pions. This set contains all significant isobars that decay into $\pi^-\pi^+$ and has been derived from a much larger set with 128 waves by requiring a minimum relative intensity of about 10^{-4}. The likelihood fit function is built from two incoherently added terms that correspond to the two values of reflectivity $\varepsilon = \pm 1$. Each term coherently sums over all partial-wave amplitudes that belong to the respective value of ε. Details on the fit model, the fitting procedure, and the results are described in Refs. [12, 13]. The division of our data set into 11 bins of t' is motivated by the very different t'-dependences of resonant and non-resonant components [15, 12]. In all partial waves studied, the intensity of non-resonant, i.e. Deck-like components [16], drops off much faster with increasing t' than that of resonances.

The result of this first PWA step reveals a number of well-known resonances with $J^{PC} = 0^{-+}$, 2^{-+}, 1^{++}, 2^{++}, and 4^{++}. They are identified by structures in the mass spectra and a mass-dependent phase that is measured against the reference wave $1^{++}\,0^+\,\rho(770)\,\pi S$. The $1^{++}\,0^+\,f_0(980)\,\pi P$ intensity shows a clear signal slightly above $1.4\,\text{GeV}/c^2$ that cannot be associated with a known 1^{++} state [see points in Fig. 1(a)]. Rapid phase rotations with respect to known resonances are observed in the signal region, independent of t' [see points in Figs. 1(d) and 1(e)]. The same feature is observed in the $\pi^-\pi^0\pi^0$ final state [17].

In the second analysis step, we use a resonance model to fit the resulting spin-density matrices simultaneously in all bins of t' and in wave-specific ranges in $m_{3\pi}$. Typically, only subsets of these spin-density matrices are fit simultaneously. In this Letter, we present such a fit using a minimal set of 3 waves, namely $2^{++}\,1^+\,\rho(770)\,\pi D$, $4^{++}\,1^+\,\rho(770)\,\pi G$, and $1^{++}\,0^+\,f_0(980)\,\pi P$. The first two waves contain the known $a_2(1320)$ and $a_4(2040)$. These two waves act as interferometers in order to search for structures in $1^{++}\,0^+\,f_0(980)\,\pi P$, where no resonances have yet been reported. For this fit, we model the amplitudes by coherent superpositions of resonant contributions that are described by relativistic Breit-Wigner (BW) amplitudes and non-resonant contributions. In the 4^{++} and 1^{++} waves, the latter are described by terms of the form $\mathscr{F}(m_{3\pi}) = e^{-c_1 q^2(m_{3\pi})}$, where c_1 is a fit parameter and q is the two-body break-up momentum for a particular isobar at the mass $m_{3\pi}$. For the non-resonant term in the 2^{++} wave, this parametrization is extended to include an explicit t'-dependence. The $a_4(2040)$ and the $J^{PC} = 1^{++}$ state are described by simple BW amplitudes, the $a_2(1320)$ by a BW with mass-dependent width, whereby the decay phase space is approximated assuming quasi-two-body decays into $80\,\%$ $\rho(770)\,\pi$ and $20\,\%$ $\eta\,\pi$.

The result of this fit is shown as curves in Fig. 1 and reveals the existence of a new axial-vector state in the $1^{++}\,0^+\,f_0(980)\,\pi P$ wave, which we introduce as $a_1(1420)$. This wave collects only $0.25\,\%$ of the total observed intensity. Its resonance interpretation is supported by the observation of a rapid phase variation by about $180°$ across the peak region with respect to the 4^{++} [see Fig. 1(d)] and 2^{++} reference waves. As illustrated in Fig. 1(e), the $1^{++}\,0^+\,f_0(980)\,\pi P$ wave shows similarly rapid phase motion also relative to the $1^{++}\,0^+\,\rho(770)\,\pi S$ wave. This indicates that the observed structure in the $f_0(980)\,\pi$ decay mode is not caused by the high-mass tails of the $a_1(1260)$, which dominates the $\rho(770)\,\pi$ wave. Our fit reveals a BW mass for the $a_1(1420)$ of $1414\,\text{MeV}/c^2$ and a width of $153\,\text{MeV}/c^2$.

The resonance-model fit is performed simultaneously in all 11 bins of t'. We allow production strengths and phases of resonances and non-resonant contributions to vary with t'. Spectral shapes and BW parameters are assumed to be independent of t'. The resulting t'-spectrum of the production intensity of the BW representing the $a_1(1420)$ is shown in Fig. 1(f). The BW intensity and that of the non-resonant contribution

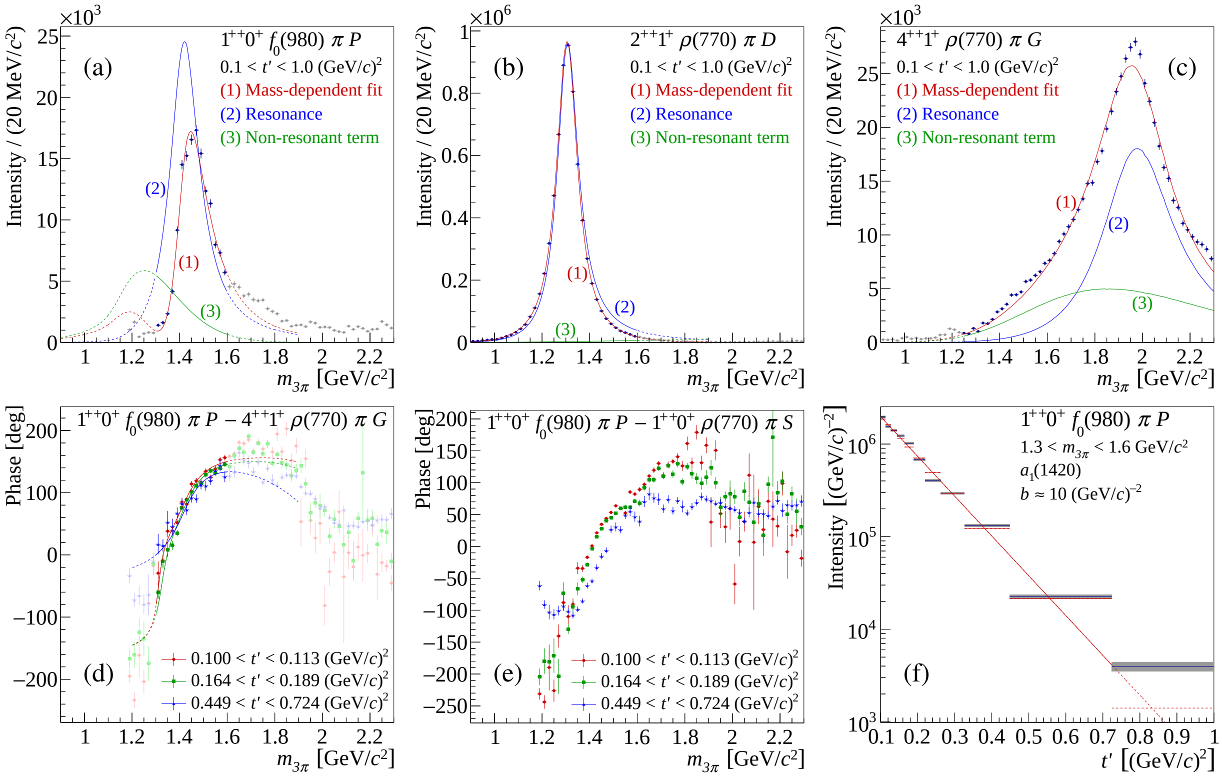

Figure 1: (Color online) Results of the PWA in 3π mass bins of $20\,\mathrm{MeV}/c^2$ width (data points with statistical errors only) showing the intensity of the three waves $1^{++}\,0^{+}\,f_0(980)\,\pi P$ (a), $2^{++}\,1^{+}\,\rho(770)\,\pi D$ (b), and $4^{++}\,1^{+}$ $\rho(770)\,\pi G$ (c), summed over t' in the region 0.1 to $1.0\,(\mathrm{GeV}/c)^2$. The curves depict the result of the resonance-model fit (red) and the individual components (blue: resonances, green: non-resonant contributions). As an example, (d) shows the relative phase between 1^{++} and 4^{++} together with the model curves and (e) the phase between two 1^{++} decay modes, in both cases for 3 t' bins. Data points not used in the resonance-model fit are indicated in gray or light colors, the extrapolated fit model by dashed curves. The t'-dependence of the $a_1(1420)$ intensity in the $1^{++}0^{+}\,f_0(980)\,\pi P$ wave, integrated over the 3π mass range from 1.3 to $1.6\,\mathrm{GeV}/c^2$, is shown in (f). The red lines represent a single-exponential fit to the data in the range $0.100 < t' < 0.724\,(\mathrm{GeV}/c)^2$.

show a steep, approximately exponential t'-dependence. Fits with a single exponential yield the slope parameters. Resonances are typically described by slope parameters $b \approx 8$ to $10\,(\mathrm{GeV}/c)^{-2}$ that are smaller than those of the non-resonant contributions with $b \approx 12$ to $15\,(\mathrm{GeV}/c)^{-2}$ [12]. The new $a_1(1420)$ has a slope parameter of $b \approx 10\,(\mathrm{GeV}/c)^{-2}$ that is similar to those of $a_2(1320)$ and $a_4(2040)$, which supports its resonance interpretation. The fact that the $a_1(1420)$ is produced with nearly constant phase offset relative to the $a_2(1320)$, independent of t', provides further support for this interpretation. As expected, the slope of the non-resonant contribution in the 1^{++} wave is steeper with $b \approx 13\,(\mathrm{GeV}/c)^{-2}$.

The 88 partial-wave set contains three independent contributions for the $\pi\pi$ S-wave isobars, namely the $f_0(980)$ with parameters taken from Ref. [18], a broad component denoted $[\pi\pi]_S$ taken from elastic $\pi\pi$ S-wave scattering [19], and the $f_0(1500)$ described by a simple BW. The $a_1(1420)$ is observed only in $1^{++}0^{+}\,f_0(980)\,\pi P$, while no signal with corresponding phase motion is seen in $1^{++}0^{+}\,[\pi\pi]_S\,\pi P$ or any other 1^{++} wave. In order to confirm the unique coupling of $a_1(1420)$ to $f_0(980)\,\pi$, we have investigated in a separate study [12, 20] the structure of the $\pi^-\pi^+$ subsystem forming 0^{++} isobars using a novel fit procedure for the partial-wave decomposition in bins of $m_{3\pi}$ and t'. Instead of describing the 0^{++} isobars by several amplitudes with fixed shape, their mass dependence is replaced by a piecewise constant function across $m_{2\pi}$, which is determined from data. We thus remove possible bias originating from the isobar model for 0^{++}. For $m_{3\pi}$ around the new resonance, a clear intensity correlation of the new $a_1(1420)$ with the $f_0(980)$ is observed within the extracted 0^{++} isobar amplitude [12].

Due to the large data set, statistical uncertainties are negligible compared to systematic effects. Therefore, we performed extensive systematic studies concerning event-selection cuts, the model used in the first step of the PWA fit, as well as wave set and parametrizations employed in the resonance-model fit. The result is stable under all these studies. The main systematic uncertainties arise from the resonance-model fit. The estimated total systematic uncertainty is $^{+15}_{-13}\,\mathrm{MeV}/c^2$ for the $a_1(1420)$ mass and $^{+8}_{-23}\,\mathrm{MeV}/c^2$ for the width. Instead of a simple BW, a mass-dependent-width BW amplitude with $f_0(980)\,\pi$ as the only decay channel yields central values for mass and width of $1433\,\mathrm{MeV}/c^2$ and $146\,\mathrm{MeV}/c^2$, respectively. Detailed simulations have shown no indication for model leakage artificially populating the $1^{++}\,0^+\,f_0(980)\,\pi\,P$ wave. This is supported by the absence of any other known isovector state at this mass.

In summary, we have performed a resonance-model fit based on a spin-density submatrix that was obtained by the so far most extensive 88-wave 3π PWA using the large COMPASS data set. Restricting this resonance-model fit to the three waves $2^{++}\,1^+\,\rho(770)\,\pi\,D$, $4^{++}\,1^+\,\rho(770)\,\pi\,G$, and $1^{++}\,0^+\,f_0(980)\,\pi\,P$, we have observed a new a_1 meson at $m = (1414\,^{+15}_{-13})\,\mathrm{MeV}/c^2$ and with a width of $\Gamma = (153\,^{+8}_{-23})\,\mathrm{MeV}/c^2$. This finding in a mass region studied by many previous experiments was made possible by the large event sample and the apparatus acceptance being essentially flat [12, 11].

The interpretation of this new state is yet unclear and, to our knowledge, it has never been predicted. Reference [21] discusses the $a_1(1420)$ as a possible two-quark-tetraquark mixed state. Scenarios were presented that allow for dynamic generation of resonances by a strong coupling of $\rho\,\pi$ and $K\overline{K}^*$ to $a_1(1260)$ [22]. On the other hand, the narrow width of only $153\,\mathrm{MeV}/c^2$, its mass value of $1414\,\mathrm{MeV}/c^2$, and its strong coupling to $f_0(980)$ that is interpretable as a $K\overline{K}$ molecule, suggest this new state to be the isospin partner of the $f_1(1420)$. The latter has a much smaller width of only $(54.9 \pm 2.6)\,\mathrm{MeV}/c^2$, which can be explained by its strong coupling to $K\overline{K}^*$ with the corresponding phase space being much smaller than that for $a_1(1420)$ decaying into $f_0(980)\,\pi$. The $a_1(1420)$ and the $f_1(1420)$ are likely to be the first observed isospin partners for a $\pi K\overline{K}$ molecular-type excitation that obey isospin symmetry. This interpretation suggests further experimental and theoretical studies of the $\pi K\overline{K}$ final state.

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