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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.

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One of the great challenges in particle physics is the understanding of how hadronic matter is constructed from its basic building blocks, quarks and gluons. Although many possibilities are allowed, which all follow the principle of confinement, almost all hadrons observed can be described by the constituent quark model. The known light-meson spectrum is presently interpreted in terms of $q\bar{q}$ 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 $q\bar{q}$ 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]. Already the existence of one system with a wave function and/or quantum numbers requiring an explanation beyond “ordinary” mesons implies the existence of a large number of additional matter states. Unless new principles for the construction of color-neutral hadrons are found, this should hold for all quark-flavour combinations.

In the sector of light mesons, the issue of exotic states remains unresolved. The lowest-mass state discussed in this context is the $f_0(980)$, which contains $n\bar{n}$ ($n = \{u, d\}$) and a dominant $s\bar{s}$ 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 to be a 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 the existence of dynamical effects 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 analyzed the diffractive reaction $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\text{recoil}}$ with the 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, see e.g. Refs. [10, 11, 12], the improvement by almost two orders of magnitude in sample size has opened a new avenue for analysis.

The COMPASS experiment [13, 14] is located at the M2 beam line of the CERN Super Proton Synchrotron. For this measurement, we used a beam of $190\,\mathrm{GeV}/c$ π^- with $96.8\,\%$ purity, impinging on a 40 cm long liquid-hydrogen target that was surrounded by a recoil-proton detector (RPD). Incoming pions were 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 t', which denotes the reduced squared four-momentum transfer to the target proton with $t' \equiv |t| - |t|_{\text{min}}$. For this measurement, t' is chosen to be in the range from 0.1 to $1.0\,(\mathrm{GeV}/c)^2$, where the lower bound is dictated by the acceptance of the RPD and the upper bound by the steep drop of the number of events with increasing t'. Outgoing charged particles are detected by the tracking system and their momenta are determined using two large-aperture magnets.

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

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. [15, 16]. 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 sum of the momenta of the outgoing particles is required to be equal to the average beam momentum within two standard deviations, i.e. $\pm 3.78\,\mathrm{GeV}/c$. 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 and $2.5\,\mathrm{GeV}/c^2$.

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 $20\,\mathrm{MeV}/c^2$ 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. [17]), while 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, i.e. 80 waves with positive and 7 with negative reflectivity as well as one non-interfering wave representing three uncorrelated pions. This set contains all significant isobars that decay into $\pi^-\pi^+$ and has been derived from a 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. [15, 16]. 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 [10, 15]. In all partial waves studied, the intensity of non-resonant, i.e. Deck-like components [18], 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 $1.4\,\mathrm{GeV}/c^2$, which cannot be associated with a known 1^{++} state [see data 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 [19].

In the second analysis step, we use a resonance model to fit the spin-density matrices resulting from the first analysis step 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 amplitude of each wave by a coherent superposition of a resonant contribution, which is described by a relativistic Breit-Wigner (BW) amplitude and a non-resonant contribution. Hence both components are allowed to interfere. In the 4^{++} and 1^{++} waves, the latter are described by terms of the form $\mathcal{F}(m_{3\pi}) = e^{-c_1\,q^2(m_{3\pi})}$, 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

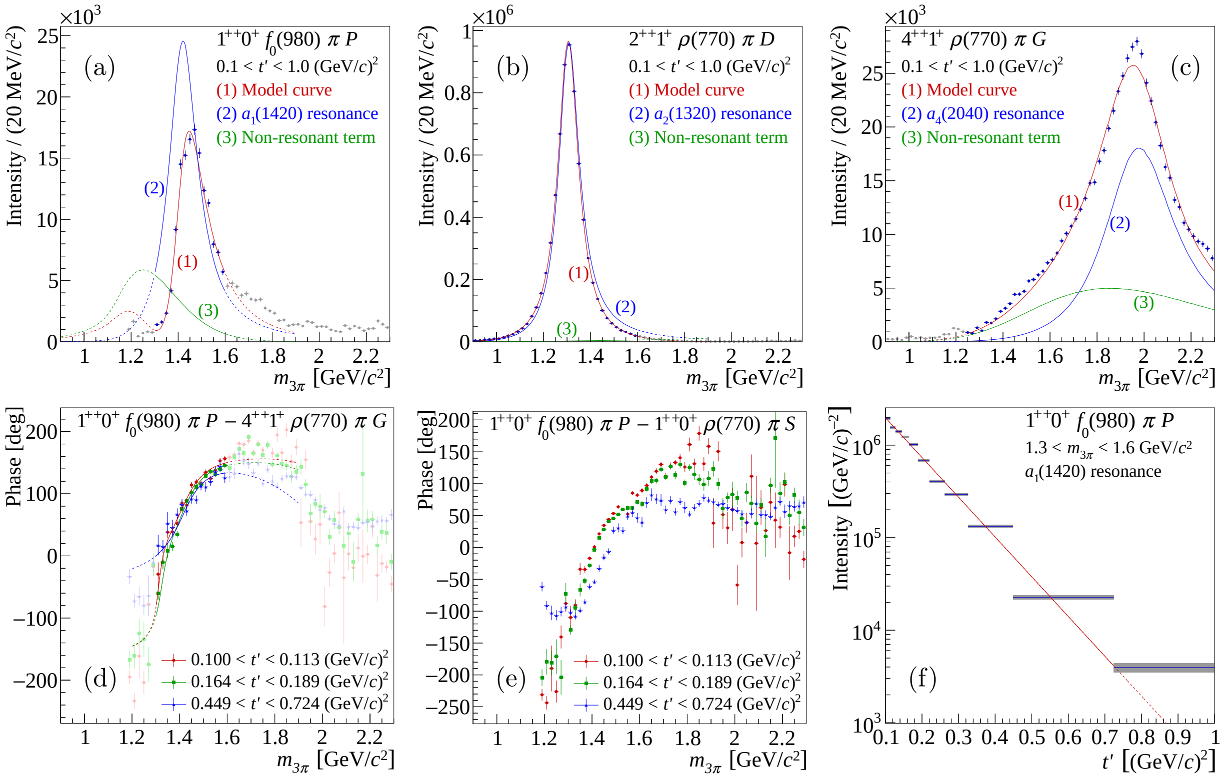

Figure 1: (Color online) Results of the PWA in 3π mass bins of $20\,\text{MeV}/c^2$ width (data points with statistical errors only). The red curves in the intensity distributions [panels (a)–(c)] represent the fit model, which is the coherent sum of resonances (blue) and non-resonant contributions (green). The fit is constrained to the mass range indicated by the continuous curves. Extrapolations of the model are shown as dashed curves. Panel (d) shows the relative phase between 1^{++} and 4^{++} together with the model curves and (e) the phase between two 1^{++} decay modes. Here, the different colors distinguish 3 exemplary t' bins. The t'-dependence of the $a_1(1420)$ intensity is shown in (f) together with the result of a single-exponential fit (red line) yielding a slope parameter of $b \approx 10\,(\text{GeV}/c)^{-2}$.

to include an explicit t'-dependence. A simple BW amplitude is used for the $a_4(2040)$ and the $J^{PC} = 1^{++}$ state, a BW amplitude with mass-dependent width for the $a_2(1320)$. In the latter, 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 Figs. 1(a) to 1(d), in which the model curves describe the data well. The blue curve in Fig. 1(a) 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 observed shift of the measured peak position with respect to the resonance position in Fig. 1(a) is due to destructive interference of the BW resonance (blue) and the non-resonant term (green). In this wave, the fit model is chosen to cover the mass range up to $1.6\,\text{GeV}/c^2$. The observed tail of the intensity at higher masses may be attributed to non-resonant contributions that are not described by the present model.

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'. Figure 1(f) shows the resulting t'-spectrum of the production intensity of the BW amplitude that describes the $a_1(1420)$. The BW intensity and that of the non-resonant contribution 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 $15\,(\mathrm{GeV}/c)^{-2}$ [15]. 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. [20], a broad component denoted $[\pi\pi]_S$ taken from elastic $\pi\pi$ S-wave scattering [21], and the $f_0(1500)$ described by a simple BW amplitude. 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 [15, 22] 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 [15].

Due to the large data set, statistical uncertainties of the extracted resonance parameters are negligible compared to systematic ones. 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. This was obtained by changing the set of waves used in the resonance-model fit, the event selection criteria, and the parametrization of the non-resonant terms. Using instead of a simple BW amplitude one with a mass-dependent width, 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. Pseudo data simulated using the full 88 waves with and without the $1^{++}\,0^+\,f_0(980)\,\pi\,P$ wave, which were subsequently analyzed with our standard 88-wave PWA, show no indication for model leakage artificially populating the $1^{++}\,0^+\,f_0(980)\,\pi\,P$ wave.

We have estimated the statistical significance of the $a_1(1420)$ signal by rescaling the statistical uncertainties of the data points such that the fit has a $\chi^2/\mathrm{ndf} = 1$ (following Ref. [9]). The decrease of the χ^2 probability of a fit performed without the assumption of a new resonance in the 1^{++} wave translates into a significance of the $a_1(1420)$ measurement, which by far exceeds the value of $5\,\sigma$. The same result is obtained when only those spin-density matrix elements are included in the χ^2 calculation, which contain the 1^{++} wave. Therefore, the result does not depend on possible imperfections in the description of the 2^{++} and 4^{++} reference waves at masses much below or above the new $a_1(1420)$.

Summarizing our analysis, 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 $m = (1414\,^{+15}_{-13})\,\mathrm{MeV}/c^2$ with a width of $\Gamma = (153\,^{+8}_{-23})\,\mathrm{MeV}/c^2$. This finding was made possible by our large event sample and, when compared to previous experiments, also by the more homogeneous acceptance of the COMPASS setup in the five phase-space variables used in the PWA [14, 16].

The interpretation of this new state is still unclear. Quark-model calculations including tetraquark states predict $nn\,\overline{nn}$ and $ns\,\overline{ns}$ iso-vector states at 1381 and 1530 MeV/c^2, respectively [23]. The molecular model for the $f_1(1420)$ proposed in Ref. [8] could possibly be extended to the isovector case. After our first announcement of the $a_1(1420)$ [24], several explanations were proposed [25, 26, 27, 28], none of them describing all features of the data. The properties of the $a_1(1420)$ suggest it to be the isospin partner of the $f_1(1420)$. This is supported by its mass value of 1414 MeV/c^2 and by its strong coupling to $f_0(980)$, which is interpretable as a $K\overline{K}$ molecule. The $a_1(1420)$ width of only 153 MeV/c^2 is narrow as compared to most other known iso-vector states, which typically have widths between 250 and 350 MeV/c^2. The much smaller width of the $f_1(1420)$ of only $(54.9 \pm 2.6)\,\mathrm{MeV}/c^2$ 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 $f_1(1420)$ may possibly be the first observed isospin partners for a $\pi K\overline{K}$ molecular-type excitation, which obey isospin symmetry. This interpretation suggests further experimental and theoretical studies of the $\pi K\overline{K}$ final state.

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