ELSEVIER

14 December 2000

PHYSICS LETTERS B

Physics Letters B 495 (2000) 284–288

www.elsevier.nl/locate/npe

An analysis of the contribution of isospin two $\pi\pi$ resonant states in the $\bar{n}p \to \pi^+\pi^+\pi^-$ annihilation reaction

OBELIX Collaboration

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Received 11 October 2000; received in revised form 2 November 2000; accepted 3 November 2000
Editor: L. Montanet

0370-2693/00/$ – see front matter
PII: S0370-2693(00)01276-4

Abstract

The results of a search for a possible evidence of a $\pi^+\pi^+$ resonant state in the $\bar{n}p \to \pi^+\pi^+\pi^-$ annihilation reaction with data collected by the OBELIX Experiment are presented. The study has been performed by means of a partial wave analysis in the frame of the isobar model. Production fractions for a possible $\pi^+\pi^+$ resonance have been evaluated. The observed effects at the $\pi^+\pi^+$ threshold may be described reasonably well by the contributions of $f_2(1270)$, $f_0(1500)$, $f_2(1565)$ and $\rho(1450)$ states and their interferences, but a meaningful statistical indication for a $\pi^+\pi^+$ scalar state at about 1400 MeV emerges from the analysis. © 2000 Published by Elsevier Science B.V.

PACS: 13.75.Cs; 12.39.Mk; 14.40.Cs
Keywords: Antineutron–proton annihilation in flight in three charged pions; Isobar model; Isospin 2 resonant states; $q^2\bar{q}^2$ exotic states

The only entry in the Particle Data Book [1] for a possible isospin two resonant state is named $X(1600)$ and it is not very well established. Evidences for such a state, observed in the $\rho\rho$ channel, were given by the CELLO and ARGUS Collaborations [2] and were based on an enhancement in the $\gamma\gamma \to \rho^0\rho^0$ cross section near threshold. A spin parity analysis assigned to it the quantum numbers $J^{\mathrm{PC}} = 2^{++}$. This observation could be interpreted by the formation of an exotic $q\bar{q}q\bar{q}$ isospin two state [3,4].

An isospin two resonance could be a good candidate as a multiquark state. According to MIT bag model [4] the $q^2\bar{q}^2$ states, with even spin and isospin, should lie close to the vector–vector mesons thresholds. Compared to their decay in the favoured vector–vector channel, the branching ratio for the decay into two pseudoscalar mesons (like $\pi\pi$) should be suppressed by a factor of about 300. The diquark cluster model [5] agrees too with these expectations. In this case the lightest $q^2\bar{q}^2$ isospin two states are foreseen in the 1350–1500 MeV mass range. Their decay should preferably lead to four pions in the final state, being the $\pi\pi$ decay mode suppressed as a consequence of the diquark cluster decay mechanism.

An early analysis of the $\bar{p}d \to \pi^+\pi^-\pi^- p_s$ annihilation reaction, based on the isobar model, was published [6] with nonconclusive evidence for the presence of a $I = 2$ state, decaying into $\pi^-\pi^-$. In the same period, dual models were applied to attempt an interpretation of the data without introducing such exotic states [7]. The analysis of Ref. [6] was performed on 2785 $\bar{p}d$ annihilation events, collected in a liquid deuterium bubble chamber and selected with a spectator proton with a momentum less than 150 MeV/c, in order to have practically pure S wave annihilation events.

In the present Letter we analyze the annihilation reaction $\bar{n}p \to 2\pi^+\pi^-$ to study the relative importance of an additional isospin two $\pi^+\pi^+$ amplitude. The possibility of observing in a clean way an isospin two state in $\bar{n}$ induced three-body exclusive reactions was discussed in Ref. [8]. Partial results of the ongoing analysis have already been reported [9]. The data sample consisted of 35118 events, collected by the OBELIX Experiment. The residual background on this sample had been estimated to be less than 0.5%; the acceptance over the full Dalitz plot is flat, within a $\sim 3\%$ modulation. All details concerning data reduction may be found in Ref. [10].

The symmetrized Dalitz plot for these data, and its $\pi^+\pi^+$ squared invariant mass projection, are shown in

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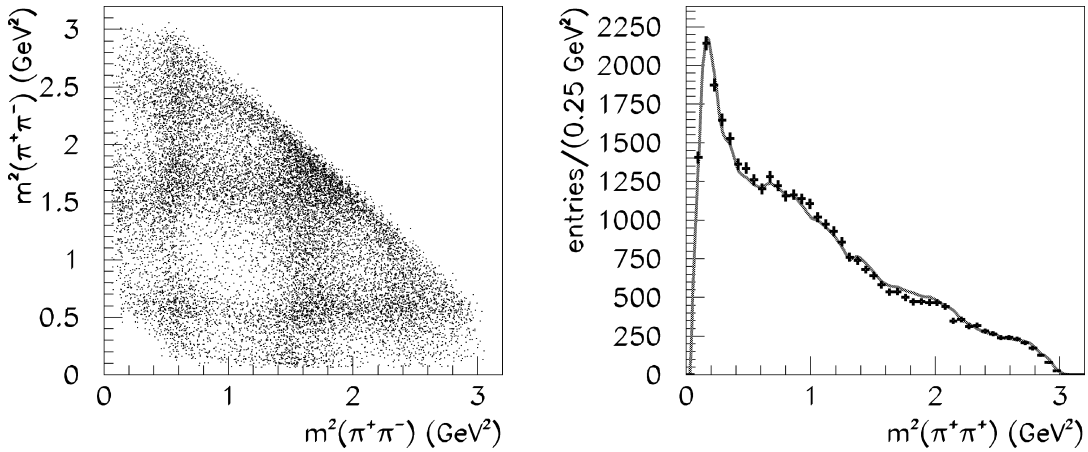

Fig. 1. Symmetrized $m^2(\pi^+\pi^-)$ Dalitz plot and its $m^2(\pi^+\pi^+)$ projection (points with errors), for the full $\bar{n}p \to \pi^+\pi^+\pi^-$ available statistics. The curve superimposed to the experimental data represents the best fit solution.

Fig. 1. Besides the horizontal/vertical bands due to the $\rho^0(770)$ and the $f_2(1270)$ resonances, and a density enhancement near the corners at about 1500 MeV, one can note a hole in the central region and a considerable accumulation at low $\pi^+\pi^+$ mass. These features are similar to those observed by Anninos et al. in Ref. [6].

A first spin-parity analysis on these data was performed primarily in order to study the nature of the enhancement around 1500 MeV [10]. In this analysis the low mass $\pi^+\pi^+$ region was not fully satisfactorily interpreted, and the possibility to introduce an isospin two amplitude to get further improvements was left open. In order to obtain an acceptable description of the low $\pi^+\pi^+$ mass sector the effects of the interferences between $f_2(1270)$, $f_2(1565)$ and $\rho(1450)$, as well as the contributions of $f_0(1370)$ and $f_0(1500)$, had to be taken into account. To this purpose, several fits were performed leaving free all masses, widths, production branching ratios and relative phases between resonances. The issues of the best solution obtained without the introduction of a $\pi^+\pi^+$ amplitude, reported in Ref. [10], were confirmed by the Crystal Barrel Collaboration in a spin-parity analysis of 35689 events collected in the $\bar{p}d \to \pi^-\pi^-\pi^+ p_s$ reaction (with $p_{p_s} < 100$ MeV/c) [11].

The amplitude for each partial wave (namely, $^1S_0$, $^3P_1$ and $^3P_2$, as the momentum of the incoming $\bar{n}$ is lower than 405 MeV/c) is usually written as a coherent sum of i isobars contributions:

$$f^J = \sum_i g_i^J A_i^J, \tag{1}$$

where A_i^J are the elementary amplitudes for each intermediate state, composed by a dynamical part F and a term Z describing the angular momenta dependence, expressed by means of Zemach covariant tensors [12]:

$$A_i^J = \sum_r Z_{ir}^{J^{\mathrm{PC}}}(p,q) F_{ir}(q). \tag{2}$$

In Eq. (2) r runs over all the possible combinations of two pions forming the i isobar state; q is the break-up momentum of the dipion and p the momentum of the recoiling pion. The f^J amplitude enters in the total amplitude composition in the formula $T_{\mathrm{tot}} = \sum_{\lambda_1,\lambda_2} |\sum_J H^J_{\lambda_1,\lambda_2} f^J_\lambda|^2$, where the λ_1 and λ_2 are the helicities of the particles in the initial state (and λ is their difference), and $H^J_{\lambda_1,\lambda_2}$ are the helicity couplings.

An isospin two amplitude was added coherently to Eq. (1) properly weighted by the isospin Clebsh–Gordan factors. Only the $I = 2$, $I_3 = 2$ component was inserted, as the $I = 2$, $I_3 = 0$ one is suppressed due to isospin composition. For the dynamical description Breit–Wigner parameterization was chosen to reproduce the contribution of a possible resonant state; as an alternative, a scattering length amplitude was intro-

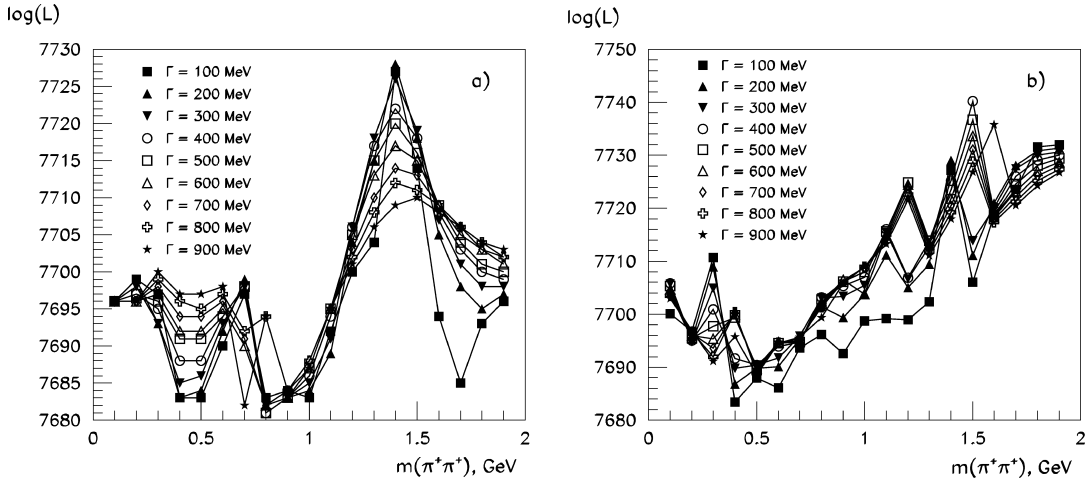

Fig. 2. log(likelihood) (ℓ in the text) values for best fit solutions as a function of $\pi^+\pi^+$ invariant mass and for fixed values of the width of the possible isospin two resonant state, in the two hypotheses (a) of a scalar resonance, or (b) of a tensor one.

duced to try to estimate the $\pi^+\pi^+$ scattering length from these data.

The fit strategy consisted in performing several series of fits using the basic set of $\pi^+\pi^-$ amplitudes, starting from the best fit solution of Ref. [10], and adding the isospin two contribution with two different choices for its spin (0 or 2). Its mass and width were allowed to vary on a discrete grid. The best fit solution achieved in each grid step was based on the minimization of $-\ell = -\log(\text{likelihood})$. In a first step the grid pitch was fixed to 100 MeV for the mass scan, and 100 MeV for the scan on Γ's. After the localization of a minimum solution, the pitches were reduced to 50, 20 or 10 MeV in the region of (m, Γ) where the minimum was found, depending on the convergence behavior of fits. Fig. 2 reports the trend of ℓ values obtained as a function of the $\pi^+\pi^+$ invariant mass, for fixed values of Γ, in the two hypotheses of a scalar $\pi^+\pi^+$ resonance (Fig. 2a), and a tensor one (Fig. 2b).

Inserting the contribution of a $\pi^+\pi^+$ spin 0 resonance, as emerges from Fig. 2a, a clear maximum of likelihood, $\ell = 7729$, is achieved for $m = (1.42 \pm 0.02)$ GeV and $\Gamma = (0.16 \pm 0.01)$ GeV. In the same picture no evidence for a $\pi^+\pi^+$ state at threshold can be observed. The increase in ℓ, as compared to the best fit solution without the isospin two amplitude, is 48 units, with four additional free parameters. An estimated relative contribution of such a state over the Dalitz plot volume is of the order of 3×10^{-3}, evaluated without taking into account interference effects (which overall amount to less than 5%). The χ^2 on the Dalitz plot, compared to $\chi^2_{\text{DP}} = 1213/1264 = 0.96$ of the best fit solution without $\pi^+\pi^+$ amplitude, improves by 155 units on 1268 degrees of freedom. The χ^2 for the $\pi^+\pi^+$ invariant mass spectrum is 1.37, to be compared to 1.69. The best fit solution for the $\pi^+\pi^+$ squared invariant mass spectrum is shown in Fig. 1, as the curve superimposed to the experimental data. The $\pi^+\pi^-$ invariant mass projection is always described almost perfectly, with $\chi^2_{\pi^+\pi^-} = 0.96$, to be compared to $\chi^2_{\pi^+\pi^-} = 0.99$.

The mass of this state is sensible to the production fraction of $\rho(1450)$. Switching off this contribution the fit deteriorates decisively, and the likelihood reaches a maximum for lower values of $\pi^+\pi^+$ system mass (about 700 MeV, with a width of 300 MeV). Several other systematic checks have been performed studying the effect of switching off some contributions and the following fit quality changes. Switching off the $f_0(1370)$ signal the $\pi^+\pi^+$ signal flattens. The $f_0(1370)$ plays basically the rôle of a broad background (its mass and width were fixed to the values found in Ref. [10] $m = (1280 \pm 55)$ MeV and $\Gamma = (323 \pm 13)$ MeV); its production branching fraction amounts to less than 10%. In the case of vanishing $f_0(1370)$ amplitude the $\pi^+\pi^+$ one almost tries to

substitute it — the maximum of likelihood is achieved for $m = (1000 \pm 100)$ MeV with $\Gamma \sim 900$ MeV. The contribution of $f_0(1370)$ to the Dalitz plot cannot be disentangled by eye. As the isospin two state is in general produced ten times less than $f_0(1370)$, it is not surprising that its contribution to the Dalitz plot is not visible as well.

The test of the second hypothesis, an isospin two tensor resonant state, does not give an indication as clear as in Fig. 2a. Fig. 2b shows a maximum of likelihood whose statistical significance is weaker. This maximum is observed at $m = (1500 \pm 50)$ MeV and $\Gamma = (400 \pm 100)$ MeV. The best fit solution delivers for the $I = 2$ tensor state a weight around 6.5×10^{-3}, about twice the one obtained in the scalar hypothesis, always without interferences effects. The overall quality of the fit is good, with $\chi^2_{\mathrm{DP}} = 0.99$; the χ^2 of the $\pi^+\pi^+$ invariant mass distribution is $\chi^2_{\pi^+\pi^+} = 1.28$.

Using in the fit a scattering length parameterization instead of a Breit–Wigner one could try to evaluate the $\pi^+\pi^+$ scattering length, leaving it as a free parameter in the fits or by means of a scan through several values on a discrete grid. The sensitivity of these fits is however not enough to obtain reliable issues, as the likelihood change is too little to allow to discriminate between different scattering length values.

In conclusion, we have observed that the introduction of a $\pi^+\pi^+$ term in s wave in the amplitude for the production of the $\pi^+\pi^+\pi^-$ final state in $\bar{n}p$ annihilation brings only a slight improvement to the quality of the fits, but has a significant effect on the likelihood variation. Instead of being located near the $\pi^+\pi^+$ threshold, as it could be expected form the Dalitz plot inspection, this 0^{++} $I = 2$ resonant state has approximately the same mass of another exotic state, the 1^{-+} hybrid observed by E852 at BNL [13] and by Crystal Barrel [14], and is moreover not far away from the tensor hybrid observed in the $\rho^0\rho^0$ channel [2]. All of these states play as different evidences of $q^2\bar{q}^2$ exotic states with different spin and parity. If confirmed, this 0^{++} signal could be the first observation of a scalar four quarks exotic state. Its decay branching fraction into $\pi^+\pi^+$ is found to be less than 0.4%. A similarly very small branching ratio is found for the $\pi^+\pi^+$ decay mode of a possible tensor state; however, its statistical significance is weaker.

Acknowledgements

The authors wish to thank prof. L. Montanet for all the hints and helpful discussions provided during the preparation of this work.

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