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PARTIAL-WAVE ANALYSIS OF THE $\omega \pi^0$ -SYSTEM AT HIGH MASSES

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(Joint CERN - IHEP experiment)

Abstract

A partial-wave analysis of the $\omega \pi^0$ -system produced in the $\pi^- p \rightarrow \omega \pi^0 n$ reaction at 38 GeV/c beam momentum has been performed. A new 5^- meson state, $\rho_5(2350)$, with a mass $M = 2330 \pm 35$ MeV and a width $\Gamma = 400 \pm 100$ MeV, is observed. The analysis also confirms the 1^- $\rho(2150)$ meson, a radial-orbital excitation of the $\rho(770)$, observed earlier by the GAMS Collaboration.

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Introduction

In this paper, the analysis of the $\omega \pi^0$ -system produced at 38 GeV/c and 100 GeV/c beam momenta in the charge-exchange reaction

$$\begin{aligned} \pi p &\rightarrow \omega \pi^0 n \\ &\hookrightarrow \pi^0 \gamma \end{aligned} \quad (1)$$

with five photons in the final state, is completed. The first stage of this study, which comprises a simplified pure-wave analysis, was completed in 1991 [1]. The main result was the observation, along with the well-known $b_1(1235)$ and $\rho_3(1690)$ mesons, of a new meson state, the $\rho(2200)$ with the quantum numbers $J^{PC} = 1^{-}, I^G = 1^{+}$. This meson, produced via the one-pion exchange mechanism (OPE), was interpreted as an orbital-radial excitation of the $\rho(770)$ meson. Its mass is close to the one expected from a simple Veneziano model [2] or from the Godfrey-Isgur model [3] for the $2^3 D_1$ excitation. The $\rho(2200)$ was observed both at 38 GeV/c (IHEP) and at 100 GeV/c (CERN). Its production cross section falls with energy quadratically as one would expect for an OPE dominated process (see Ref. [1] for details).

The next stage of this study, which is the subject of this paper, is a mass-independent partial-wave analysis (PWA) of the $\omega \pi^0$ -system at low momentum transfer in the mass region well above the $b_1(1235)$, where OPE processes dominate. For $\omega \pi^0$ masses $M_{\omega \pi^0} > 1.4$ GeV the number of events as a function of the upper $|t|$ -cutoff, as well as the angular distributions in the ω helicity frame, behave as one would expect for an OPE-dominated process [1]. Thus, only events with $M_{\omega \pi^0} > 1.4$ GeV and $|t| < 0.1$ (GeV/c)² were used for PWA, and the assumption of OPE being the dominant mechanism was made. Other cuts and event selection procedures are the same as described in Ref. [1].

The set of partial waves used in this analysis was restricted to $1^{-}, 3^{-}$ and 5^{-} (OPE dominance). PWA was applied to the angular distributions in the Gottfried-Jackson frame only. Both a simplified model without absorption (pure OPE) and a poor-man's absorption model [4] were used to fit the experimental angular distributions.

The PWA results presented in this paper are based on the 38 GeV/c data obtained with the GAMS-2000 spectrometer during 1983, 1984 and 1987 runs at the IHEP accelerator. The 100 GeV/c GAMS-4000 data, being ten times lower in statistics, are not used in this analysis.

1. Pure OPE partial-wave formalism

In the case of pure OPE ($\rho_{00} = 1$) the differential cross section of reaction (1) in the Gottfried-Jackson frame for three interfering waves is expressed as:

$$\frac{d^2 \sigma}{dz d\phi_{\gamma}} \sim \left| A_1 c_1 P_1^1(z) + A_3 c_3 P_3^1(z) e^{i\varphi_{31}} + A_5 c_5 P_5^1(z) e^{i\varphi_{51}} \right|^2. \quad (2)$$

Here $z = \cos\vartheta_{GJ}$, and ϕ_{TY} is the Treiman-Yang angle. $P_J^1(z)$ is the associated Legendre function of degree J normalized to unity by the c_J . A_J is the absolute value of the J^- -wave amplitude and ϕ_{J1} is the phase shift between the J^- and the 1^- waves. The overall phase of the 1^- -wave can be chosen arbitrarily.

The cross section (2) does not depend on ϕ_{TY} . It can be expanded in a set of Legendre polynomials of even order : $d\sigma/dz = a_0 P_0(z) + a_2 P_2(z) + \dots + a_{10} P_{10}(z)$, where a_i are some functions of the set of parameters $P = (A_1, A_3, A_5, \phi_{31}, \phi_{51})$.

The problem of determining these five parameters from six measurables a_i (which are the moments of the angular distribution in the Gottfried-Jackson frame) is complicated, the resulting equations are non-linear and not independent. There exists a two-fold non-trivial ambiguity of the PWA solutions. The only variable that can be determined unambiguously is A_5 , the highest-spin amplitude.

2. Fitting procedure

To find both sets P of PWA solutions and to determine their statistical errors, a combination of analytical and numerical methods has been used. First, the mass spectrum of the $\omega\pi^0$ -system is subdivided into a set of 50 MeV wide bins. For each mass bin an *uncorrected* angular distribution $dN/d\cos\vartheta_{GJ}$ is built and stored as a histogram with a $\cos\vartheta_{GJ}$ bin width of 0.1.

For each mass bin the efficiency of the apparatus and of the physical cuts is calculated as a function of $\cos\vartheta_{GJ}$ with the event-by-event Monte Carlo method. OPE distributions are assumed for all variables. The resulting efficiency as a function of $\cos\vartheta_{GJ}$ is stored as an histogram with the same bin width as for that of the experimental angular distribution.

The set of variables P in each mass bin is determined by fitting the experimental histogram with the theoretical distribution (2) multiplied by the efficiency histogram. The maximum likelihood method is used for the fit. A Poisson distribution of the number of events in a bin is assumed for the experimental data. Adjacent bins of the angular distribution histogram are assumed to be non-correlated. This is a reasonable approximation since the width of the bin is in general much larger than the detector resolution in $\cos\vartheta_{GJ}$.

The minimization program MINUIT [5] has been used for the optimization. MINUIT optimization ends up in one of the two possible maxima of the likelihood function, which determines the parameters of one solution with their errors. The other solution is first calculated analytically using the parameters of the first one. This is used as an input (close to the second maximum) for MINUIT optimization and error analysis. Such a combination of analytical and numerical methods guarantees convergence of the optimization process, and gives statistically correct values and errors of the parameters P for both solutions.

The above procedure has been applied to each $\omega\pi^0$ mass bin. Both solutions are determined in each bin. The mass dependences of the partial amplitudes and of the phases have thus been determined for both solutions.

The physical solution has been selected by requiring dominance of the peak in the amplitude squared of the 3^- -wave, corresponding to the $\rho_3(1690)$, a well established meson [6].

3. Pure OPE partial waves

The 3^- amplitude squared for the physical solution (normalized to the total number of events corrected for efficiency) is plotted in Fig. 1. The $\rho_3(1690)$ peak indeed dominates the spectrum. A fit with a sum of a Breit-Wigner curve and a polynomial background gives the following mass and width for this resonance :

$$\begin{aligned} M &= 1670 \pm 25 \text{ MeV}, \\ \Gamma &= 230 \pm 65 \text{ MeV}, \end{aligned} \tag{3}$$

which are consistent with the PDG values [6].

The production cross section $\sigma(\pi^- p \rightarrow \rho_3 n) \cdot \text{BR}(\rho_3 \rightarrow \omega\pi^0) = 1.13 \pm 0.20 \text{ } \mu\text{b}$ agrees with our previous result [1]. Here and in what follows the cross section is given for the whole t -range, being extrapolated with the OPE t -dependence [1] (40% was added to the cross sections measured in the $|t| < 0.1 \text{ (GeV/c)}^2$ range in order to account for the OPE cross section above the $|t|$ -cutoff).

The normalized 1^- amplitude squared for the physical solution is shown in Fig. 2. The dominating structure in this spectrum is a broad peak with the following parameters :

$$\begin{aligned} M &= 2140 \pm 30 \text{ MeV}, \\ \Gamma &= 320 \pm 70 \text{ MeV}. \end{aligned} \tag{4}$$

The parameters (4) are close to our preliminary results [1]. In what follows, this meson will be referred to as the $\rho(2150)$ (instead of $\rho(2200)$).

The production cross section of the $\rho(2150)$, $\sigma(\pi^- p \rightarrow \rho n) \cdot \text{BR}(\rho \rightarrow \omega\pi^0) = 0.30 \pm 0.06 \text{ } \mu\text{b}$, is higher than our preliminary result [1]. Current PWA shows that most of the "background" in the $\omega\pi^0$ mass spectrum under the $\rho(2150)$ -peak is in fact the result of interference between the $\rho_3(1690)$ and the $\rho(2150)$. With the interference taken into account the cross section increases by a factor two.

Finally, the normalized 5^- amplitude squared is shown in Fig. 3. This amplitude is the same for both PWA solutions, as mentioned above. The mass spectrum displays a pronounced peak at 2.35 GeV. Some activity at 1.7 GeV may reflect a leakage from the huge $\rho_3(1690)$ resonance. A fit with a sum of one Breit-Wigner curve and a polynomial background (Fig. 3) gives the following parameters for this resonance (in what follows referred to as the $\rho_5(2350)$ meson) :

$$\begin{aligned} M &= 2330 \pm 35 \text{ MeV}, \\ \Gamma &= 400 \pm 100 \text{ MeV}. \end{aligned} \tag{5}$$

The $\rho_5(2350)$ production cross section is $\sigma(\pi^-p \rightarrow \rho_5 n) \cdot \text{BR}(\rho_5 \rightarrow \omega\pi^0) = 0.07 \pm 0.02 \mu\text{b}$.

The behavior of the relative phase between the 1^- and 3^- waves, as well as that between the 3^- and 5^- waves (Fig. 4), shows two phase-flips near the resonance maxima, as one would expect for two distant resonances. The relative phase between the 1^- and 5^- waves (not shown) is quite smooth because both $\rho(2150)$ and $\rho_5(2350)$ are broad, overlapping significantly in mass.

The mass of the new meson is close to what one would expect from a simple Regge model for the 5^- ground-state (Fig. 5). Some evidences for the 5^- -wave in this mass region were reported previously from a PWA of the $\pi\pi$ -system in the $p\bar{p}$ production and annihilation reactions [6].

4. Partial-wave analysis for OPE with absorption

An attempt to perform the PWA for OPE with an additional absorption term was also made. The Ochs-Wagner modification of the poor-man's absorption model (PMA) [4] was used. In this model, the assumption of S-channel nucleon spin-flip dominance adds ϕ_{TY} -dependent terms to the expansion of the differential cross section in the Gottfried-Jackson frame : $d^2\sigma/dz d\phi_{TY} = \alpha_0 Y_0^0(z) + \dots + \alpha_{10} Y_{10}^0(z) + \beta_2 Y_2^1(z, \phi_{TY}) + \dots + \beta_{10} Y_{10}^1(z, \phi_{TY})$. Here Y_{2l}^m are the normalized real spherical harmonics.

The Ochs-Wagner model also superimposes certain constraints on the moments α_j and β_j (see Refs. [4,8] for details) :

$$\beta_j/\alpha_j \sim \sqrt{j(j+1)} / M_{\omega\pi^0} \quad (6)$$

(for $j > 2$), which shows that the main contribution of the absorption terms is observed for lower masses and higher spins. So, one would expect the largest distortion of the pure OPE results for the $\rho_3(1690)$ (low mass and relatively high spin) and for the $\rho_5(2350)$ (high mass, but very high spin), while for the $\rho(2150)$ the correction should be small.

The analytical analysis of the non-linear equations relating amplitudes, phases and absorption factor with 11 parameters α_i, β_i was not carried out. The PWA equations with absorption are solved for the highest wave amplitude 5^- only. An extension of the technique described in section 2 for the two-dimensional $[\cos\vartheta_{GJ}, \phi_{TY}]$ histograms is used to determine this amplitude in each mass bin. It is found that all odd moments of angular distributions are compatible with zero, as well as the moments of Y_{2l}^m with $m \neq 0, 1$. It is also observed that the experimental data follow the dependence (6) rather well.

The structure at 2.35 GeV in the 5^- -wave mass spectrum survives after introduction of the absorption terms. The parameters of its fit with a Breit-Wigner resonance coincide within the errors with the pure OPE results (5). The contribution of the absorption terms in the $\rho_5(2350)$ mass region is found to be about 10%. However, the quality of the maximum likelihood fit of the high-mass data, dominated by the $\rho_5(2350)$, improves significantly : the corresponding χ^2/NDF value drops from 2 to 1

with the absorption taken into account. Quantitatively, the results on the absorption corrections are in agreement with the $\pi^- p \rightarrow \pi^+ \pi^- n$ and $\pi^- p \rightarrow \pi^0 \pi^0 n$ PWA at high energies [7, 8].

Using the scale of absorption corrections for the $\rho_5(2350)$ and formula (6), it has been shown that the contribution of the absorption terms in the $\rho(2150)$ region is less than 3%, and thus it is safe to neglect it. The absorption terms contribution in the $\rho_3(1690)$ region is about 9%.

Conclusions

A new 5^- state, the $\rho_5(2350)$, shows up in the partial-wave analysis of the $\omega\pi^0$ -system both in the pure OPE and in the PMA approximations. The existence of the 1^- $\rho(2150)$ meson is confirmed. The parameters and the production cross sections of these resonances as well as those of the $\rho_3(1690)$ meson are measured. The $\rho(2150)$ and the $\rho_5(2350)$ masses are in a good agreement with the Veneziano formula [2], the Godfrey-Isgur model [3] and Regge model predictions.

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Figure captions

- Fig. 1 : Normalized amplitude squared of the 3^- -wave. The histogram shows the PWA results, the solid curve is the fit with a sum of a Breit-Wigner resonance and a polynomial background (dashed curve). The arrow indicates the tabular $\rho_3(1690)$ mass.
- Fig. 2 : Same as in Fig. 1, but for the 1^- -wave. The mass bin is doubled. The arrows indicate the $\rho_3(1690)$ and $\rho(2150)$ masses.
- Fig. 3 : Same as in Fig. 2, but for the 5^- -wave. The arrows indicate the $\rho_3(1690)$ and $\rho_5(2350)$ masses.
- Fig. 4 : Phase shifts between the 3^- and 1^- waves (a), and the 5^- and 3^- waves (b). The arrows indicate the $\rho_3(1690)$, $\rho(2150)$ and $\rho_5(2350)$ masses.
- Fig. 5 : Regge trajectory for the ρ , ω and f mesons (mass squared versus spin). The dots with the error bars are the experimental data (ρ_5 is the result of this work), the straight line is the least square fit to the data.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5