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STUDY OF THE $f_0(995)$ RESONANCE IN THE $\pi^0\pi^0$ DECAY CHANNEL

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 (Joint CERN - IHEP experiment)

Abstract

A high-statistics study of the $\pi^0\pi^0$ -system produced in the $\pi\pi \rightarrow \pi^0\pi^0n$ reaction at 38 GeV/c has been carried out at the IHEP accelerator using the GAMS-2000 multiphoton spectrometer. A partial-wave analysis which includes S, D₀, D, and D₄ waves has been performed in the $|t|$ -range up to 1 (GeV/c)². The S*/f₀(980) resonance is seen as a dip in the S-wave amplitude at small $|t|$. A distinct peak of a 997 ± 5 MeV mass and a 48 ± 10 MeV width is observed in the S-wave at $|t| > 0.3$ (GeV/c)². The production cross sections are measured.

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Introduction

In this work the GAMS Collaboration continues the analysis of the $\pi^0\pi^0$ system produced in the charge-exchange reaction

$$\begin{aligned} \pi^- p &\rightarrow \pi^0\pi^0 n \\ &\quad \searrow 4\gamma \end{aligned} \quad (1)$$

at 38 GeV/c π^- beam momentum. The previous studies of this reaction [1,2] had been pursued at low momentum transfers ($|t| < 0.2$ (GeV/c)²) where the one-pion exchange (OPE) contribution is enhanced. A strong upper limit on the production cross section of the $f_2(1810)$ resonance, claimed by Cason et al. [3] in the D_0 -wave¹, had been set; and the $f_2(1270)$ production cross section had been measured in the D_0 , D_+ , and D_- waves. In the present work a partial-wave analysis (PWA) of the $\pi^0\pi^0$ system has been carried out in the 4-momentum transfer range extending up to 1 (GeV/c)². The goal is to study the t -behavior of the S-wave in the $\pi^0\pi^0$ mass region around 1 GeV. The presence of the $S^*/f_0(980)$, the lightest scalar meson ($J^{PC} IG = 0^{++}0^+$) which has been a puzzle since the 1970's [5], in particular, makes this region very interesting.

The measurements have been performed at the IHEP 70 GeV proton accelerator. The multiphoton hodoscope spectrometer GAMS-2000 [6] was used to detect four photons in the final state of the reaction (1). A total of $2 \cdot 10^6$ $\pi^0\pi^0$ -events were collected during two one-month runs (1982 and 1984). The distance L between the target and GAMS, that was 12 m during the first run, has been reduced to 4.3 m in the second run, improving the efficiency at high masses at the cost of a somewhat lower mass resolution. Also, the accumulated statistics in the second run was four times larger than those in the first one. The experimental setup, the measurement conditions, the calibration of the spectrometer, and the event reconstruction procedure have been described in details elsewhere [6, 7].

1. Event selection

A number of criteria are used in order to reject physical and instrumental backgrounds during event selection. Tighter selection criteria are applied in the $|t| < 0.2$ (GeV/c)² region, in which 85% of the $\pi^0\pi^0$ -events are accumulated. At such a high statistics, PWA is very sensitive to any instrumental distortion in photon detection as well as to efficiency uncertainties.

First, cuts are imposed on all 4- γ events selected by the GAMS event reconstruction program. Events with photons, that have an impact distance to the beam axis smaller than 30 mm, are eliminated in order to suppress the background produced in the central GAMS cells by the heavy load due to the high beam intensity. At low $|t|$ this cut is increased to 45 mm. All events with any photon having an energy less than 0.6 GeV are rejected. The total energy measured in GAMS must lie within $\pm 12\%$ of the beam energy. A higher photon threshold energy is used in the 1982 run where the

instrumental background is somewhat larger. The total energy in GAMS has to lie within $\pm 8\%$ of the beam energy for this run.

The $\pi^0\pi^0$ -events are then selected among other possible 4- γ channels ($\eta\pi^0$, $\eta\eta$, ...) using a kinematical 3C fit (masses of both mesons and of the recoil neutron being fixed). Events which better fit $\pi^0\pi^0$ channel are used for the further analysis if $\chi^2 < 8.3$ (CL = 96%). Very asymmetrical π^0 decays are excluded ($\cos \theta_\gamma > 0.9$, θ_γ being the polar angle of the π^0 decay in its rest frame, with the z-axis pointing in the boost direction). At low $|t|$, an extra cut is applied: $\cos \theta_{GJ} < 0.85$, where θ_{GJ} is the Gottfried-Jackson polar angle. The final $\pi^0\pi^0$ sample is virtually background-free [2].

Fig. 1 shows the $\pi^0\pi^0$ mass spectra obtained after 3C fit, both at low $|t|$ and high $|t|$. The low momentum transfer region shows, along with the dominating $f_2(1270)$ meson [2], a dip below 1 GeV (Fig. 1a, 1984 data). The dip disappears with increasing $|t|$, and a shoulder appears in the same mass region (Fig. 1b). A clear peak, instead of the shoulder, is observed in the 1982 high-resolution data (Fig. 1c). Its mass and width are 995 ± 10 MeV, and 50 ± 10 MeV, respectively (the spectrometer mass resolution being taken into account).

2. Partial-wave analysis

The 1984 run data have been submitted to PWA in order to determine the quantum numbers of the observed structure. The detection efficiency for the reaction (1) events is computed by Monte Carlo using a bank of real showers [8]. The very same programs and selection criteria used in the experimental data analysis are applied to the $\pi^0\pi^0$ events generated by Monte Carlo. The efficiency is parametrized as a function of the θ_{GJ} and ϕ_{TY} angles in the Gottfried-Jackson frame, of the $\pi^0\pi^0$ invariant mass, and of $|t|$ in the form of a four-dimensional Fourier series as described in Ref. [9]. At small momentum transfer it reaches a maximum when $\cos\theta_{GJ} = 0$ ($\approx 50\%$ at a mass of 1 GeV). It drops to zero when $\cos\theta_{GJ}$ approaches 1. The region of zero efficiency disappears with increasing $|t|$, and the efficiency dependence on $\cos\theta_{GJ}$ becomes smoother providing more favorable conditions for PWA.

The PWA includes S, D_0 , D_- , and D_+ waves (the contribution of higher waves is negligible in the mass range under study [10]). It is carried out in several $|t|$ -intervals, up to 1 (GeV/c)². The efficiency in each interval is integrated over t according to the experimental t -dependence. The $\pi^0\pi^0$ -events are grouped into 20 MeV mass bins. The events for which the efficiency drops below 2% are discarded. Angular distributions in each mass bin are fitted independently with the maximum likelihood method using two different procedures. In the first one, the two-dimensional $[\cos\theta_{GJ}, \phi_{TY}]$ histograms are fitted; in the second one, the event-by-event procedure is used. Both procedures give similar results, within the statistical errors.

3. PWA results

Two non-trivial solutions are found in each t -interval. The first one is characterized by unphysically large D -waves near the threshold of reaction (1). For the second (physical) solution the S and D_0 waves (the latter being a tail of the $f_2(1270)$) give the major contributions to the cross section in the 1 GeV mass region at low $|t|$. The intensities of the D - and D_+ waves are about 10% of that of the D_0 -wave. The relative contribution of the latter decreases with increasing $|t|$, while the D_+ -wave intensity becomes comparable with that of the S -wave in this mass region.

The S -wave in both low- $|t|$ and high- $|t|$ regions is shown in Fig. 2 for the physical and unphysical solutions. At low momentum transfer, $|t| < 0.2$ (GeV/c)², both solutions are in a good agreement with the previous results [1]. The physical solution exhibits a dip below 1 GeV (Fig. 2a), the result of the $S^*/f_0(980)$ destructive interference with the background. A rapid variation of the phase shift between the S and D_0 waves confirms the presence of the $S^*/f_0(980)$ resonance (Fig. 2b). A broad structure is observed at 1.2 GeV with a width of about 300 MeV; it can be naturally associated with the $\epsilon/f_0(1300)$ meson [5]. Its mass agrees with that of the S -wave resonance seen both in the $\eta\eta$ -system [11] and in previous studies of the $\pi^0\pi^0$ -system [1, 12].

The S -wave behavior changes significantly when $|t|$ increases. The region between 0.2 (GeV/c)² and 0.4 (GeV/c)² is rather complex, the two solutions are close to each other. Thus, their unique identification is difficult. The picture becomes much more clear at large momentum transfer, $|t| > 0.4$ (GeV/c)² (Fig. 2c). The physical solution exhibits a distinct peak at 1 GeV. The phase shift between the S and D waves (the $|D_0|^2$ is almost zero here) drops in the peak region showing a typical resonance behavior (Fig. 2d).

4. Masses, widths and production cross sections

For further analysis of the narrow $0^{++}0^+$ state observed in the S -wave at large $|t|$, the t -dependence of its production cross section has been measured. The present statistics allows to determine only the cross section, integrated over a wide t -interval. The lower edge of the interval, $|t|_{\min}$, is varied from 0.3 (GeV/c)² to 0.5 (GeV/c)² in 0.05 (GeV/c)² steps, with the upper edge being fixed at 1 (GeV/c)². The PWA shows a clear S -wave resonance at 1 GeV in each of these intervals (Figs. 3a-e). The peak disappears at $|t|_{\min} < 0.3$ (GeV/c)².

A fit of the S -wave amplitude squared has been performed in the 0.62 GeV to 1.36 GeV mass region with a relativistic Breit-Wigner resonance (with an energy dependent width) interfering with a polynomial background (Fig. 3). The Breit-Wigner function is convoluted with a Gaussian describing the mass resolution of the GAMS-2000 spectrometer ($\sigma_M/M \approx 2\%$ at $M = 1$ GeV). The mass and the width of the resonance are found to be

$$\begin{aligned} M &= 997 \pm 5 \text{ MeV}, \\ \Gamma &= 48 \pm 10 \text{ MeV}. \end{aligned} \tag{2}$$

The production cross section of this resonance, integrated over t , is shown in Fig. 4. (the cross section is twice as large if the interference between the resonance and the background is not taken into account properly). The $\pi^- p \rightarrow \eta n$ reaction is used for normalization. This reaction was well studied at 40 GeV [13, 14]. The $\eta \rightarrow 2\gamma$ events have been detected in the present experiment along with the reaction (1) events.

The parameters of the observed S-wave resonance (2) have been compared with those of the $S^*/f_0(980)$ meson seen in the S-wave at low momentum transfer. A fit of $|S|^2$ (Fig. 3f) is carried out at $|t| < 0.2$ (GeV/c)² in the mass range 0.78 GeV to 1.18 GeV (the S-wave is poorly defined at lower masses due to a low efficiency). The same fitting procedure is used as for the high $|t|$ data. A mass of 960 ± 10 MeV and a width of 95 ± 20 MeV are obtained for the $f_0(980)$. The production cross section is found to be $\sigma(\pi^- p \rightarrow f_0(980)n) \cdot \text{BR}(f_0(980) \rightarrow \pi^0\pi^0) = 64 \pm 8$ nb ($|t| < 0.2$ (GeV/c)²). This corresponds to $\sigma \cdot \text{BR} = 75 \pm 10$ nb for the whole t -range, taking into account the OPE t -dependence of the cross section. The OPE dependence fits well the cross sections measured both at low $|t|$ and high $|t|$ (Fig. 4).

Note that the parameters of the $S^*/f_0(980)$ given in Ref. [5] were obtained through the analysis of complicated interference pictures with many channels involved. The width of this resonance remains uncertain (40 MeV to 400 MeV). Contrary to this, the parameters (2) of the scalar meson, observed in the present work at high $|t|$ as a narrow peak in the mass spectrum (Figs. 1-3), are defined in a model-independent way.

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Figure captions

- Fig. 1 : Mass spectrum of the $\pi^0\pi^0$ -events after 3C fit, not corrected for efficiency :
- a) $|t| < 0.2$ (GeV/c)², $L = 4.3$ m; b) $|t| > 0.2$ (GeV/c)², $L = 4.3$ m;
 - c) $|t| > 0.2$ (GeV/c)², $L = 12$ m.
- Fig. 2 : $|S|^2$ of the physical solution (solid histogram) and of the unphysical one (dashed histogram) (a), and relative phase of the S and D_0 waves, physical solution, at $|t| < 0.2$ (GeV/c)² (b); c) same as in a) but for $0.4 < |t| < 1$ (GeV/c)²; d) relative phase of the S and D. waves, physical solution, same $|t|$ -interval as in c).
- Fig. 3 : $|S|^2$ at large momentum transfer. $|t|_{\min}$: a) 0.30 (GeV/c)², b) 0.35 (GeV/c)², c) 0.40 (GeV/c)², d) 0.45 (GeV/c)², and e) 0.50 (GeV/c)². The upper $|t|$ -limit is 1 (GeV/c)². Solid lines show the result of the fit with a Breit-Wigner curve and a polynomial background, the interference being taken into account. Dotted lines show the background, dashed curves correspond to the Breit-Wigner resonances. f) same but at low momentum transfer, $|t| < 0.2$ (GeV/c)².
- Fig. 4 : Production cross sections of the $S^*/f_0(980)$ (o) and of the S-wave resonance (2) (•), integrated over t from $|t|_{\min}$ to 1 (GeV/c)², as a function of $|t|_{\min}$. Curve shows the OPE dependence : $\sigma \sim \int t(t-m_\pi^2)^{-2} e^{bt} dt$, $b = 4.7$ (GeV/c)², normalized at the $S^*/f_0(980)$ point.

Fig. 1

Fig. 2

Fig. 3

Fig. 4