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OBSERVATION OF A SPIN 6 NEUTRAL MESON $r(2510)$

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ABSTRACT

In a high statistics experiment (200 events/nanobarn) performed at the 70 GeV IHEP accelerator, a new dipion resonance has been observed in π^-p collisions at 38 GeV/c momentum. The gamma-rays in reaction $\pi^-p \rightarrow M^0n$, $M^0 \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$ have been detected in the hodoscope spectrometer GAMS-2000. The new meson, $r(2510)$, has a mass (2510 ± 30) MeV/c², a width (240 ± 60) MeV/c² and spin-parity $J^{PC} = 6^{++}$. The production cross-section of the f , h and r mesons decreases exponentially with spin like $\exp(-0.9J)$.

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1. INTRODUCTION

The present work is devoted to the study of $\pi^0\pi^0$ states with masses up to $3 \text{ GeV}/c^2$ produced in the charge exchange reaction

and to the search for a spin 6 meson amongst these. Former studies of such processes have led to the discovery of the h -meson with spin 4 [1,2]. The investigation of large spin multiplets is of great interest for the systematics of elementary particles and is important for the understanding of the confinement mechanism [3].

This reaction has been chosen as a favorable way to observe heavy mesons. Only even parity M^0 mesons may be produced in this process so that the successive resonances are well separated on the $M_{\pi\pi}$ mass scale and that the lighter ones do not conceal the heavier ones which are much less intense. This reaction is dominated by the one pion exchange mechanism (OPE) [1,4,5]. This simplifies considerably the determination of the M^0 spin through the angular distribution of its decay. The absorption corrections, which complicate the analysis at small mass values, disappear in the region of heavy mesons.

However, the study of reaction (1) presents experimental difficulties associated with the need to detect the four gammas with high efficiency and precision for the kinematical reconstruction.

2. DATA TAKING AND HANDLING

The experiment has been performed with $38 \text{ GeV}/c$ negative pions. The experimental lay-out, the apparatus and the data handling procedure are identical to the ones used earlier [6,7]. The final decay products of reaction (1) have been identified with the hodoscope spectrometer GAMS-2000 which is capable of measuring the energy and the coordinates of a large number of gamma-rays simultaneously, allowing to determine the mass and the momentum of the decaying particles.

The sensitivity of the experiment is 200 events of type (1) per nanobarn. The statistics is one order of magnitude larger than in all previous works ($3 \cdot 10^5$ f mesons and $4 \cdot 10^4$ h mesons being recorded).

Ten million events have been analysed off-line with existing reconstruction programs [7]. The background in the selected events of type (1) is practically negligible [6]. The kinematical properties of the $\pi^0\pi^0$ systems have been determined in a 3C fit (fixing the mass of the neutral pions and that of the recoil neutron). Further analysis has been restricted to events with $\chi^2 < 10$ (98% probability). The invariant mass and the angular distribution $N(M_{\pi\pi}, \theta_{GJ})$ of reaction (1) in the Gottfried-Jackson system have been evaluated for the final data, taking into account the detection efficiency.

The variation of efficiency with the mass $M_{\pi\pi}$ and the angle θ_{GJ} has been obtained by Monte Carlo calculations using a real shower data base [7]. The efficiency decreases monotonically with increasing $\cos \theta_{GJ}$ and is defined essentially by the geometrical acceptance of the spectrometer. In the $h(2030)$ -meson region, an interval $0 < \cos \theta_{GJ} \leq 0.95$ is covered. At larger masses, $M_{\pi\pi} \approx 2.5 \text{ GeV}/c^2$, the upper limit is ≈ 0.9 . Model calculations of the resolution of the spectrometer as a function of $M_{\pi\pi}$ give $\sigma_M = 40 \text{ MeV}/c^2$ in the f-meson region and $\sigma_M = 60 \text{ MeV}/c^2$ in the h-meson region. The $\cos \theta_{GJ}$ resolution is within 0.01 to 0.02.

3. MASS AND ANGULAR DISTRIBUTIONS

Fig. 1a shows the mass spectrum of dipion systems produced in reaction (1) where clear peaks corresponding to the f and h mesons are seen. This spectrum includes only events with $\cos \theta_{GJ} > 0.5$, i.e. asymmetrical M^0 decays where high spin states are more clearly visible [1]. The mass region above the f-meson is displayed in more detail in Fig. 1b. A statistically significant structure, corresponding to a possible $\pi\pi$ resonance with a mass $\approx 2.5 \text{ GeV}/c^2$, appears to the right of the h-meson peak. The events, after background subtraction, are shown in the insertion.

The decay angular distributions have been analysed in order to establish the nature of the observed structure in the mass spectrum and to see whether this could be the resonance with spin 6, next to h-meson. As already mentioned, reaction (1) is dominated by OPE. The concentration of events at small momentum transfer (Fig. 2) is a characteristic of this mechanism which is determined mainly by the pion propagator. Only the events with $-t < 0.2 \text{ (GeV/c)}^2$ have been retained in order to suppress the contribution of processes other than OPE. This represents 90% of the total number of events in reaction (1).

In the framework of OPE, the angular distribution of decay (1) may be described by

$$N(M_{\pi\pi}, \theta_{GJ}) \sim \left| \sum_{\ell} T_{\ell} q^{\ell+1/2} P_{\ell}(\cos \theta_{GJ}) \right|^2 \quad (2)$$

where $P_{\ell}(\cos \theta_{GJ})$ is the Legendre polynomial of order ℓ , $q = (M_{\pi\pi}^2 - 4m_{\pi}^2)^{1/2}/2$ is the pion momentum in the M^0 rest frame, and T_{ℓ} is the amplitude of the partial wave with orbital angular momentum ℓ (ℓ even). For known resonances, maxima and minima which are characteristic of the dominant P_{ℓ}^2 contribution are clearly seen in the angular distributions [1].

These features of the angular distribution $N(M_{\pi\pi}, \theta_{GJ})$ allow to increase considerably the sensitivity of the search for high spin resonances by a proper choice of the considered angular interval. The comparison of the functions P_6^2 and P_4^2 shows that the region of $\cos \theta_{GJ} \approx 0.8$ is favorable to enhance the spin 6 meson. In this region P_6^2 has a narrow maximum while P_4^2 is nearly minimum so that the background due to the intense h-meson is relatively small.

This method to analyse the mass spectrum allows to perform simultaneously a cross-check by considering the neighbouring angular region with $\cos \theta_{GJ} \approx 0.65$ where $P_6^2 \approx 0$ and P_4^2 has a maximum so that the signal due to spin 6 states is strongly suppressed.

The mass spectra for both chosen angular intervals are displayed on Fig. 3. Fig. 3a shows a clear peak in the mass region above the h-meson, coincident with the structure of Fig. 1b, but now more prominent due to the suppression of the h-meson background.

In order to describe the experimental mass and angular distributions it is thus necessary to introduce a new meson, denominated r(2510), besides the known f(1270) and h(2030) mesons. Its spin $J = 6$ is confirmed by a cross-check : the mass spectrum for events with $0.625 < \cos \theta_{GJ} < 0.7$ (Fig. 3b) does not show a resonance structure above the h-meson.

This also follows from a partial wave analysis of the experimental distribution $N(M_{\pi\pi}, \theta_{GJ})$ using expression (2). In general, the solution is not unique but the various solutions give the same value for the intensity of the highest ℓ wave as it is entirely determined by the momentum of the highest spherical harmonic : $|T_\ell|^2 \sim \langle Y_{\ell 0}^2 \rangle$.

The value of $|T_\ell|^2$ obtained by limiting partial waves to $\ell \leq 4$ in the mass region up to the r(2510)-meson describes well the spin 4 resonance (Fig. 4). The resulting mass and width of the h-meson agree with those measured earlier : $M_h = (2020 \pm 20) \text{ MeV}/c^2$, $\Gamma_h = (240 \pm 40) \text{ MeV}/c^2$ (taking into account the spectrometer resolution). The intensity of the $\ell = 6$ partial wave corresponding to the r(2510)-meson with spin 6, obtained in the same way, has a pronounced resonance character (Fig. 4).

4. CHARACTERISTICS OF THE r(2510)-MESON

The mass and the width of the observed mesons have been determined from the data represented in Figs. 1, 3 and 4. They agree with the tabulated values for the f and h mesons. The mass and the full width of the r(2510)-meson are :

$$M_r = (2510 \pm 30) \text{ MeV}/c^2, \quad \Gamma_r = (240 \pm 60) \text{ MeV}/c^2.$$

The r(2510) quantum numbers are :

$$J=6; \quad P, C \text{ and } G \text{ are even.}$$

The observed decay mode allows isospin $I=0$ or 2 . This second possibility is exotic and up to now no charge 2 meson has yet been observed. So, $I=0$ is preferred and $r(2510)$ should be considered as a member of the $J=6$ $SU(3)$ nonet. In favor of this interpretation is also the fact that $r(2510)$ is aligned on the Chew-Frautschi plot with isosinglet states (f and h) belonging to $J=2$ and $J=4$ nonets (Fig. 5).

The $r(2510)$ -meson production cross-section in reaction (1) has been obtained by normalization to the known cross-section for reaction $\pi^-p \rightarrow fn$ at the same energy, $(5.1 \pm 1.3) \mu b$ [8] :

$$\sigma(\pi^-p \rightarrow rn) \cdot BR(r \rightarrow \pi^0\pi^0) = (50 \pm 16) \text{ nb.}$$

From these data, the branching ratio for the decay of $r(2510)$ into $\pi\pi$ may be evaluated in the framework of OPE [9] : $BR(r \rightarrow \pi\pi) = (6 \pm 2)\%$.

The h -meson production cross-section in reaction (1), obtained in the same way, is $(240 \pm 70) \text{ nb}$. Fig. 6 shows that $\sigma \cdot BR$ decreases exponentially with increasing spin J :

$$\sigma(\pi^-p \rightarrow M^0n) \cdot BR(M^0 \rightarrow \pi^0\pi^0) \sim \exp(0.9J) \quad (3)$$

in agreement with calculations [9,10].

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Figure captions

- Fig. 1 a) Mass spectrum of $\pi^0\pi^0$ systems produced in reaction (1) with $\cos \theta_{GJ} > 0.5$; b) same spectrum on an enlarged scale. The curves on this figure and the following ones are the results of fits made with a Breit-Wigner expression with a dynamical width [6]. In the insertion is shown the excess of events relatively to the curve describing the f-meson and h-meson contributions.
- Fig. 2 a) t-distribution of reaction (1) events in the mass region of the f and h mesons. The curves correspond to one pion exchange : $d\sigma/dt \sim -t(t-m_\pi^2)^{-2} \exp(bt)$, where $b = 5 \text{ (GeV/c)}^{-2}$ and 7 (GeV/c)^{-2} for the f-meson and h-meson, respectively; b) integrated t-distribution of events in the region of the r(2510) peak (insertion on Fig. 1). The curve represents the OPE dependence with $b=7 \text{ (GeV/c)}^{-2}$.
- Fig. 3 Mass spectrum of $\pi^0\pi^0$ systems in reaction (1): a) selection of events with $0.75 < \cos \theta_{GJ} < 0.8$ favoring the observation of states with spin $J=6$. The dashed curve shows the spectrum corresponding to half of the statistics ($0.775 < \cos \theta_{GJ} < 0.8$) to illustrate the statistical significance of the results; b) same spectrum for $0.625 < \cos \theta_{GJ} < 0.7$, where the partial wave corresponding to $J=6$ is suppressed.
- Fig. 4 Intensity (in arbitrary units) of the $\ell=4$ and $\ell=6$ partial waves. The peaks correspond to the h(2030) and r(2510) mesons.
- Fig. 5 Chew-Frautschi plot for the f, h and r mesons. The straight line is given by $J = aM^2+b$.
- Fig. 6 Value of σ_{BR} for the f, h and r mesons. The errors shown do not take into account the normalization uncertainty (25%). The straight line is the exponential dependence (3).

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6