EVIDENCE FOR A SPIN-5 BOSON RESONANCE AT 2300 MeV

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ABSTRACT

Evidence is given for the existence of a spin-5 boson resonance from the analysis of the reaction $\pi^- p \rightarrow K^+ K^- n$ at 62 GeV incident momentum. A simplified amplitude analysis with a Breit-Wigner ansatz leads to a mass of 2307 ± 6 MeV and a width of 245 ± 20 MeV. The quantum numbers of the resonance are $J^P = 5^-$, $C = -1$, and very probably $I^G = 1^+$.

(Submitted to Physics Letters)

1. INTRODUCTION

The reaction $\pi^- p \rightarrow K^+ K^- n$ has been studied at 62 GeV incident momentum with the ACCMOR wire spark chamber spectrometer in the H1 beam of the CERN Super Proton Synchrotron (SPS). The data were recorded together with the reactions $\pi^- p \rightarrow \pi^+ \pi^- n$ and $\pi^- p \rightarrow \bar{p} p n$. The main aim of these experiments was to study the s-dependence of the production of known boson resonances and to explore the mass region above 2 GeV invariant mass, about which there exists only modest information.

A first indication of a new resonance with a mass around 2.20 GeV has been reported by Evangelista et al. [1] from the analysis of the reaction $\pi^- p \rightarrow K^+ K^- n$ at 10 GeV.

2. APPARATUS AND TRIGGER SELECTION

Figure 1 shows the layout of the spectrometer. Incident beam particles interact in a 50 cm liquid-hydrogen target. The multiplicity of charged forward-going secondaries has been selected by a multiwire proportional chamber hodoscope P1 and a 32-element counter hodoscope P2/3. The charged secondary particles were momentum analysed by the spectrometer formed by two magnets ($220 \times 60 \text{ cm}^2$ area, $\int B d\ell = 8 \text{ kG}\cdot\text{m}$; $150 \times 50 \text{ cm}^2$ area, $\int B d\ell = 20 \text{ kG}\cdot\text{m}$) and five sets of wire spark chambers with magnetostrictive read-out. The π^0 mesons were detected by lead-sandwich scintillation counters F around the target, G in front of the first magnet, H in front of the second magnet, and a γ -calorimeter at the end of the set-up. Two multicell atmospheric pressure Čerenkov counters Č1, Č2 served to identify secondary particles. The second counter, filled with helium, had a pion threshold of 17 GeV and a kaon threshold of 62 GeV, and served to identify π -pairs. The first Čerenkov counter served mainly to discriminate between kaons and protons.

During the first half of the data-taking period, the latter counter was filled with a N_2 -He mixture with a kaon threshold of 27 GeV and a proton threshold of 52 GeV. The counter was fully efficient ($> 96\%$) at half the beam momentum but did not allow discrimination between K and p above 55 GeV (between 52 and 55 GeV,

pulse-height discrimination was used). During the second half of the data-taking period the threshold was raised to 31 GeV and 58 GeV for kaons and protons, respectively, thus losing some events where both kaons had about half the beam momentum, but allowing the unambiguous separation of K and p in the high-momentum range. The information of the Čerenkov counters was not included in the trigger, but was recorded for off-line analysis together with the spark positions.

The geometrical acceptance of the detector allowed the study of the complete decay angular range up to 3.0 GeV KK mass and a four-momentum transfer squared (t) less than 3 GeV^2 . In the first 50 MeV above threshold, some events are lost owing to reconstruction problems.

Incident π , K, $\bar{p}$ beam particles were tagged with two differential and one threshold Čerenkov counter.

The trigger condition for this experiment was an incoming beam particle coinciding with two and only two signals in the counter hodoscopes and the absence of any signal in the lead-sandwich scintillation counters F and G.

3. DATA PROCESSING AND EVENT SELECTION

A total of 5×10^6 triggers were recorded and processed off-line with our analysis program (TENPRO). A total of $\sim 250,000$ two-prong candidates were found. The sample is dominated by $\pi\pi$ pair production. With the information from the two Čerenkov counters, $\pi^+\pi^-$, K^+K^- , and $p\bar{p}$ final states were separated. For the K pairs we required no signal in Č2, thus separating the dominant $\pi\pi$ channel, and a signal in Č1, thus separating nearly all $p\bar{p}$ pairs.

As has already been mentioned, pulse-height information was used in a small momentum range above p threshold in order to further suppress the $p\bar{p}$ contamination. We also required that the faster particle passed the spark chamber set IIIc at its predicted position. This condition is necessary for rejecting pion pairs where one pion had a momentum below the pion threshold of Č1 of 8.5 GeV or did not pass the second magnet, and the other pion interacted in the mirrors or

exit window of Č1 or the entrance window of Č2, thus sending only slow particles through Č2.

Owing to small inefficiencies of the lead-sandwich scintillation counters, we also recorded a small fraction of events with additional π^0 production. The distribution of the missing mass was completely dominated by a peak at the neutron mass but extended to high missing-mass values. After applying an appropriate cut, we estimate that our sample contains less than 3% of $K^+K^-\pi^0$ events. From calibrations and the analysis of the $\pi^+\pi^-n$ and $p\bar{p}n$ channels, we estimate that our uncorrected data contain about 3% $\pi^+\pi^-$ pairs and about 7% $p\bar{p}$ pairs. Both backgrounds accumulate in the high mass region. The final sample contains 12,000 events.

The events were corrected for acceptance losses by randomly rotating them around their beam particle direction. Small variations due to beam energy spread, vertex distribution, etc., were also taken into account. Below 2.5 GeV invariant mass the acceptance corrections are small and typically around 20%. The events were further corrected for decay in flight losses of the kaons, secondary interactions in the hydrogen target, and losses from δ -rays and neutrons detected by the lead-sandwich scintillation counters. Finally the data were corrected for the $\pi\pi$ and $p\bar{p}$ background. With the known efficiency values of the two Čerenkov counters and the information of the π pair and $p\bar{p}$ pair spectra, we corrected the K pair sample in all four kinematic variables, m , t , $\cos \theta$, ϕ (θ and ϕ being the decay angles of the K^- in the KK rest system; here we choose the Gottfried-Jackson reference frame). Owing to the accumulation of background at high KK masses, the data are less reliable above 2.5 GeV.

4. EXPERIMENTAL RESULTS

Figure 2a shows the observed and corrected mass spectrum for $|t| < 0.5 \text{ GeV}^2$. Below 1.050 GeV some events are lost owing to reconstruction problems (vertex badly defined for low t and small opening angle between secondary tracks).

Below 2.5 GeV we observe four peaks. The first three can be associated with the (fA_2f'), the g , and the h mesons, while the fourth peak around 2.25 GeV indicates the presence of a new state.

The spherical harmonic moments $N\langle Y_L^M \rangle$ of the decay angular distributions have been calculated in the t -channel reference frame as a function of mass. Figure 3 shows the $M = 0$ moments up to $L = 12$.

The $N\langle Y_L^0 \rangle$ moments with even L show in first order the structure of a series of overlapping resonances with increasing spin and decreasing spacing, while the $N\langle Y_L^0 \rangle$ moments with odd L indicate the structure of interfering resonances. The $N\langle Y_6^0 \rangle$ shows a first peak at the g meson and successive shoulders at the positions of the h meson and the new state. The $N\langle Y_8^0 \rangle$ moment shows a peak at the position of the h meson and again a shoulder at the position of the new state. The $N\langle Y_{10}^0 \rangle$ moment has a small positive value at the position of the new state, but because of the large errors, one cannot conclude unambiguously that this new state has spin 5, while the $N\langle Y_9^0 \rangle$ moment -- the interference term between a spin-4 and a spin-5 state in the absence of any higher states -- shows the pattern of two overlapping resonances, thus establishing the spin of the new state to be 5. The moments $N\langle Y_{11}^0 \rangle$ and $N\langle Y_{12}^0 \rangle$ are consistent with zero up to 2.4 GeV mass.

The $M = 1$ moments are an order of magnitude smaller than the $M = 0$ moments. The large statistical errors of the $M = 1$ moments prevent the observation of any detailed structure. On the average they have opposite sign compared to the $M = 0$ moments, and decrease relative to the $M = 0$ moments with increasing mass. This behaviour has been observed in π pair, K pair and $p\bar{p}$ pair production at 17 GeV, and has been interpreted as an increase of pure pion exchange (OPE) for increasing pair mass [2]-[4]. The $M = 1$ moments are shown in refs. [5] and [6]. Except in the (fA_2) region the moments with $M \geq 2$ were all found to be consistent with zero. The differential cross-section $d\sigma/dt$ does not vary in shape between 1.5 and 2.5 GeV and $|t| < 0.5 \text{ GeV}^2$, and follows exactly the pattern observed in π pair and K pair production at lower energies. Therefore we feel justified in assuming one-pion exchange as the dominant production mechanism.

5. POSITION AND WIDTH OF THE NEW RESONANCE

In order to obtain an estimate for the position and width of the new spin-5 state, we have attempted to fit simultaneously the mass dependence of the $M = 1$ and $M = 0$ moments up to $L = 10$ in fig. 3, and the mass spectrum of fig. 2b between 1.56 and 2.46 GeV mass and $|t| < 0.5 \text{ GeV}^2$, using t-channel helicity amplitudes.

An energy-dependent analysis was performed under the assumption that the production is dominated by OPE with small and equal contributions of natural and unnatural helicity-one amplitudes. This condition, together with the absence of helicity amplitudes $|\lambda| \geq 2$, is justified by the absence of moments with $M \geq 2$ in the M, t range quoted above. We further assume dominance of nucleon spin-flip amplitudes, and that for spin ℓ the helicity-one amplitudes T_+^ℓ, T_-^ℓ and the helicity-zero amplitudes T_0^ℓ are in phase, and that their ratio is a smooth function in M . Systematic deviations from these assumptions have recently been found in the low-mass $\pi\pi$ region [7]. The deviation decreases with increasing mass and is of marginal significance already in the g-meson region.

In the mass region analysed, we assume that the dominant structures are caused by resonating partial waves with spin $\ell = 3, 4$, and 5. Thus we parametrized the helicity $\lambda = 0$ amplitudes T_0^ℓ by relatively real Breit-Wigner expressions:

$$T_0^\ell = \pm C^\ell \frac{M}{\sqrt{q}} \frac{M_R^\ell \Gamma^\ell}{M^2 - (M_R^\ell)^2 - i M_R^\ell \Gamma^\ell}, \quad \ell = 3, 4, 5,$$

where

C^ℓ = parameters to be determined by the fit containing various normalizations;

M_R^ℓ, Γ^ℓ = mass and width of the resonance of spin ℓ to be determined by the fit;

M, q = invariant KK mass and centre-of-mass momentum in the KK rest system;

$\Gamma^\ell = \Gamma_0^\ell [q/q(M=M_R)]$.

For the spin-3 and spin-4 partial waves, we added a slowly varying background term of the form:

$$T_0^\ell = (a^\ell + ib^\ell) \sqrt{M - M_R} \quad \text{for } M \geq M_R ; \quad \ell = 3, 4 .$$

This background allows for possible deviations from the Breit-Wigner function far above the resonance position.

The amplitudes for the background partial waves with $\ell = 0, 1, 2$ were parametrized in the following general form:

$$T_0^\ell = D^\ell + iE^\ell , \quad \ell = 0, 1, 2 .$$

The D^ℓ and E^ℓ are polynomials of M :

$$D^\ell = d^{\ell,1} + d^{\ell,2} M + \dots ;$$

$$E^\ell = e^{\ell,1} + e^{\ell,2} M + \dots .$$

For $\ell = 0, 1$ we used polynomials up to M , while for $\ell = 2$ a polynomial up to M^2 was necessary.

The amplitudes T_+^ℓ and T_-^ℓ were parametrized by

$$|T_+^\ell| = |T_-^\ell|$$

and

$$T_-^\ell = T_0^\ell \sqrt{\ell(\ell+1)} \frac{F}{1-1.7 M^2} ;$$

F is a constant to be determined by the fit.

This empirical formula, common to all partial waves, has been successfully used to describe the amplitudes for π , K , $p\bar{p}$ pair production above 1 GeV mass in $\pi^- p$ interactions at lower incident energies [4,8].

With the amplitudes defined above, we simultaneously fitted the mass spectrum and moments with a χ^2 minimization program determining the free parameters M_R^ℓ , Γ^ℓ , C^ℓ , a^ℓ , b^ℓ , $d^{\ell,i}$, $e^{\ell,i}$, and F . For the fit we binned the mass spectrum in steps

of 30 MeV (the mass resolution varies from $\sigma = 15$ MeV at 1.55 GeV to $\sigma = 30$ MeV at 2.5 GeV) and the moments in steps of 60 MeV. Neglecting the contribution to the errors from acceptance correction and background correction, we obtained a χ^2 per degree of freedom of 1.44. The result of the fit and the shape of the 3^- , 4^+ , and 5^- waves are displayed as solid curves in figs. 2b and 3. The masses and widths of the resonances were found to be:

$$M^3 = 1699 \pm 5 \text{ MeV} ; \quad \Gamma^3 = 219 \pm 14 \text{ MeV}$$

$$M^4 = 1978 \pm 5 \text{ MeV} ; \quad \Gamma^4 = 243 \pm 16 \text{ MeV}$$

$$M^5 = 2307 \pm 6 \text{ MeV} ; \quad \Gamma^5 = 245 \pm 20 \text{ MeV}$$

During the various fits with different parametrizations, we found that the positions of the resonances were very stable, while the values for the width varied substantially, in particular for the h meson. We also tried fits associating spin-4 or spin-6 to the state around 2.3 GeV but found unacceptable χ^2 values.

Various background parametrizations have been tried, particularly for the spin-2 background. Nearly all reasonable fits require a broad d-wave bump around 1800 MeV. The addition of a spin-6 background slightly improved the fit above 2 GeV but did not change the position and width of the new state significantly. A rising spin-6 background is necessary if one extends the fit above 2.46 GeV mass. The parameters for the background and partial waves are of no essential importance for the parameters of the spin-5 state and details will be discussed elsewhere [6].

The signs of the amplitude T^3 , T^4 , and T^5 cannot be determined, but all three have the same sign. The parameters for the g and h mesons are in reasonable agreement with previous measurements [9]. Also, the values for the spin-5 state agree within the errors with the results of ref. [1] using only a Breit-Wigner parametrization of their mass spectrum.

For the spin-5 state we determined a cross-section of 29 ± 6 nb for the mass range of 2.175 to 2.445 GeV and $|t| < 0.5 \text{ GeV}^2$. For the constant F -- connecting the T_-^ℓ and T_+^ℓ amplitudes with the T_0^ℓ amplitudes -- we obtained a value of $F = 0.34 \pm 0.02$.

6. QUANTUM NUMBERS

From the spin-parity relation of $P = (-1)^L$ for the KK system, it follows that the spin-5 state has negative parity. From $C = (-1)^L$ it follows that C is also negative. Depending on the isospin, the G-parity is either positive or negative. As we observe no deviation in $d\sigma/dt$ nor in the dominance of the $M = 0$ over the $M = 1$ moments in the spin-5 region as compared to the g and h regions, the production of the new state will very likely also proceed by OPE, thus restricting the G-parity to be positive and the isospin to be 1. The quantum numbers of the new state are then

$$J^P = 5^-, \quad C = -1 \quad \text{and very likely} \quad I^G = 1^+.$$

This will be the fifth state on an exchange-degenerate ρ trajectory. On a Regge trajectory linear in M^2 , one expects a spin-5 state around 2.26 GeV.

Acknowledgements

We wish to thank the SPS crew for providing the beam and the technical support. We further thank Carole Ponting for the preparation of this paper and Gaby Waltermann for assistance in the off-line computing.

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Figure captions

- Fig. 1 : Layout of the experimental apparatus: H_2 = hydrogen target; MNP, BBC = spectrometer magnets; I, II, IIIa, IIIb, IIIc = wire spark chamber sets; F, G, H = lead-sandwich scintillation counters; P1, P2/3 = hodoscopes for multiplicity selection; Č1, Č2 = gas Čerenkov counters for secondary particle identification. The hodoscope P4/5 was replaced by a γ calorimeter at an early stage of the experiment.
- Fig. 2a : Invariant KK mass spectrum for the reaction $\pi^- p \rightarrow K^+ K^- n$ at 62 GeV incident momentum. $|t| < 0.5 \text{ GeV}^2$. The histogram shows raw data. Error bars show the spectrum after acceptance and various losses and background corrections. The solid line denotes the results of the fit.
- Fig. 2b : Expanded spectrum between 1.575 and 2.475 GeV. Contribution of the dominant resonances shown as solid lines.
- Fig. 3 : Spherical harmonic moments in the t-channel reference frame as a function of mass. The solid lines denote results of the fit.

Fig. 1

Fig. 2

Fig. 3