EXPERIMENTAL PROOF OF THE EXISTENCE OF THE A_1 MESON

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ABSTRACT

In partial wave analyses of the $(\pi^-\pi^-\pi^+)$ system, substantial shape changes of the 1^+S ($\rho\pi$) intensity as a function of t , and relative phase changes of $\approx 90^\circ$, provide compelling evidence for a resonant A_1 of mass ≈ 1280 MeV and width ≈ 300 MeV.

(Submitted to Physics Letters B)

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1. INTRODUCTION

In the naïve quark model, a p-wave $q\bar{q}$ system gives rise to two $I = 1$, $J^P = 1^+$ mesons. The positive G parity member of the lowest lying system, the $B(1235)$, has long been established in the $\omega\pi$ decay mode. The negative G parity A_1 , presumed to decay into $\rho\pi$, has defied certain identification, principally because of the presence of the diffractive dissociation of the incident pion through the Deck process into the same final state. Attempts to use charge and hypercharge exchange reactions [1] to find the A_1 have suffered from low statistics and the complication of $I = 0$ final states. Small cross-sections also weaken attempts to use baryon exchange reactions [2], although here there have been specific claims for a resonance at a mass ~ 1.04 GeV.

The present experiment on diffractive production of the $(\pi^-\pi^-\pi^+)$ system has yielded very high statistics (an order of magnitude greater than was obtained in the best previous experiment [3]), in a wider range of momentum transfer. Partial wave analysis of this data results in unambiguous detection of the A_1 meson.

2. THE DATA AND ANALYSIS

The data in this publication came from 598 128 events of the reaction

$$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$$

taken in three approximately equal samples with the WA3 forward spectrometer [4,5]. Two of these, at 63 GeV and 94 GeV incident momenta, have data down to zero momentum transfer squared to the proton (standard trigger), and a partial wave analysis has been performed in the regions $0.0 \leq |t'| \leq 0.05$ and $0.05 \leq |t'| \leq 0.7$ GeV². As no dependence on centre-of-mass energy has been found, the results from these samples have been combined, assuming uncorrelated errors, within the t' ranges specified, except for the purpose of cross-section calculations. The third sample, at 94 GeV only, was biased in favour of higher momentum transfers (high t' trigger), and here the data has been analysed in the ranges $0.16 \leq |t'| \leq 0.30$ and $0.30 \leq |t'| \leq 0.7$ GeV². The three-pion mass spectra in these momentum transfer intervals are shown elsewhere [4].

The nomenclature for the contributing states is $J^P_{LM}{}^\eta$, where the angular momentum, L , between the odd pion and neutral isobar is given in spectroscopic notation. The dominant natural parity exchange mode $M^\eta = 0^+$ is presumed unless stated in full.

3. RESULTS

The 1^+S ($\rho\pi$) intensities in the four t' regions fitted may be seen in Fig. 1.

From low to high momentum transfers the qualitative change is from a broad peak in the 1.1 GeV region to a flat top from 1.1 to 1.3 with rapid fall-off to, finally, a narrower peak in the 1.3 GeV region. It is certainly clear that a resonance alone could never describe these phenomena, and it is equally clear that no simple diffractive model, always giving a peak below 1.1 GeV, can duplicate this behaviour either.

For comparison with previous analyses [3] the 1^+S0^+ cross-section in the region $1.0 \leq M(3\pi) \leq 1.2$ GeV integrated over all t' is shown for the three data samples in Fig. 2 as a function of incident momentum, p . A fit with the form $\sigma \propto p^{-n}$ yields an exponent $n = 0.42 \pm 0.04$, similar to the value $n = 0.43 \pm 0.06$ obtained for the 2^-S0^+ ($f\pi$) intensity, where there is comparatively strong resonance production [6].

If there is any resonant content in the 1^+S mass spectra it should be evident from a sizeable change in the phase of this partial wave. Although there is some small t dependence in the relative phases, for the purposes of examining mass-dependent phase changes, the data of all samples have been averaged in Fig. 3.

The relative phases with respect to the ($\epsilon\pi$) waves 0^-S (Fig. 3a) and 1^+P (Fig. 3b) show, at most, excursions of $\approx 30^\circ$ and are compatible with previous experiments [3]. However, as found with coherent production off nuclei [7], there is a large phase increase of 1^+S with respect to 0^-P ($\rho\pi$) (Fig. 3c). In addition the other ($\rho\pi$) reference wave, 2^-P , indicates similar 1^+S phase movements in the region of 1.3 GeV (Fig. 3d). A resonant A_3 above 1.6 GeV/ c^2 decaying into this channel [6] causes a downturn of relative phase at higher masses.

Either the phases of 1^+S , 1^+P and 0^-S are increasing with 3π mass or the phases of 0^-P and 2^-P are decreasing. The first possibility is shown to be correct by reference to the $(1^+S0^+ - 2^+D1^+)$ relative phase (Fig. 3e, solid points), which initially rises but then shows a rapid backward movement caused by the A_2 meson [4] in the reference wave. If the phase for a Breit-Wigner resonance with the observed A_2 parameters is added to this phase difference, the result (dotted points) confirms the forward motion of the 1^+S phase by $\approx 80^\circ$ in the 1.1-1.5 GeV region.

The systematic change in shape of the 1^+S intensity as a function of t' and the observed large phase increase give a strong indication of production of a resonant object of mass ≈ 1.3 GeV with a rather flatter t' distribution than that of a coherent background. To further understand the data it is necessary to use a model in which a background amplitude provided by the Deck process is rescattered through a resonance which also may be produced directly.

4. MODEL-DEPENDENT FITS

The solid lines of Fig. 4 (a to d) show the results of separate fits in each of the four t' regions to a model amplitude of the form [8]

$$B e^{i\delta} \left(\cos \delta + \frac{\alpha}{k} \sin \delta \right) + \frac{A}{k} e^{i\delta} \sin \delta ,$$

where A represents a direct production amplitude and B is a Deck amplitude. The latter is taken as a simple one-pion exchange term with the pion propagator modified by an exponential form factor chosen to reproduce the variation with t' of the 1^+S intensity near 1 GeV. The elastic $\rho\pi$ phase shift, δ , is given by a Breit-Wigner amplitude and k is the $\rho\pi$ phase space. The constant α was taken as 0.4, a value appropriate to the very small $|t'|$ region of Fig. 4a.

The four simultaneous fits to intensity and a reference phase ($2^+D1^+ - A_2$ phase) are excellent and yield consistent resonance parameters. The A_1 mass is ≈ 1280 MeV and the width is ≈ 300 MeV. Direct production appears to be with an exponential momentum transfer slope $\approx 7 \text{ GeV}^{-2}$ to be compared to the over-all intensity in this region which has a slope of $10.1 \pm 0.9 \text{ GeV}^{-2}$.

The dashed curves in Fig. 4 show the contribution of the Deck term alone. These fitted intensities agree within 30% with absolute calculations, except for $|t'| > 0.3$, where the fitted B term is negligible. Even if normalized upwards, it is clear that the Deck component invariably peaks too soon and falls too slowly to be compatible with these data. In addition, the simple one-pion exchange amplitude has a constant phase and even if the propagator is Reggeized the resulting phase increase is $\leq 30^\circ$ from 1.1 to 1.5 GeV in 3π mass.

The illustrated fits have an arbitrary production phase between B and the direct term A. Fitted values were $\approx 40^\circ$, but acceptable χ^2 values were obtained, with similar resonance parameters, when this phase was constrained to be zero. In an alternative parametrization, essentially that of Basdevant and Berger [9], this production phase is taken as zero, but δ is the sum of a resonant phase shift and that of a repulsive scattering length term. The resulting fits required little direct production and roughly twice as much Deck intensity as the original fits, but were again very good and yielded similar resonance parameters.

Uncertainties in the normalization of the Deck amplitude and in the correct form to be employed for the elastic phase shift δ make it impossible to determine in a model-independent way the magnitude and phase of the direct production term, but all fits in all t' regions require an A_1 resonance of mass 1280 ± 30 MeV and width 300 ± 30 MeV, regardless of the details of the model.

5. CONCLUSIONS

The absolute magnitude of the $1^+S_0^+$ ($\rho\pi$) partial wave and its substantial change of shape as a function of momentum transfer is incompatible with diffractive Deck mechanisms as the sole contribution. A broad peak at ≈ 1.3 GeV, seen better at higher $|t'|$, and an accompanying large phase change in the data provides compelling evidence for a resonant A_1 . Fits with a model in which such a state is produced directly and through rescattering give excellent χ^2 and require a mass 1280 ± 30 MeV and width 300 ± 30 MeV. These data do not support a resonance in the region of 1.0 to 1.1 GeV.

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Figure captions

- Fig. 1 : Intensities of the $1^+S_0^+$ partial wave: for summed 63 and 94 GeV results with standard trigger: (a) $0.0 \leq |t'| \leq 0.05$; (b) $0.05 \leq |t'| \leq 0.7 \text{ GeV}^2$; and for 94 GeV results with high t' trigger (c) $0.16 \leq |t'| \leq 0.30$. (d) $0.30 \leq |t'| \leq 0.7 \text{ GeV}^2$.
- Fig. 2 : Cross-section for the $1^+S_0^+$ intensity for $1.0 \leq M(3\pi) \leq 1.2 \text{ GeV}$ as a function of incident momentum.
- Fig. 3 : Average relative phase changes for all data showing $1^+S_0^+$ ($\rho\pi$) with respect to (a) 0^-S ($\epsilon\pi$), (b) 1^+P ($\epsilon\pi$), (c) 0^-P ($\rho\pi$), (d) 2^-P ($\rho\pi$), (e) $2^+D_1^+$ ($\rho\pi$). The dotted points on the latter plot show the effect of a correction for a pure A_2 Breit-Wigner resonance.
- Fig. 4 : Results of "Resonant A_1 plus rescattered Deck" fits in 1^+S intensity and phase with respect to $2^+D_1^+$, A_2 phase subtracted.
(a) $0.0 \leq |t'| \leq 0.05$, (b) $0.05 \leq |t'| \leq 0.7$,
(c) $0.16 \leq |t'| \leq 0.3$, (d) $0.3 \leq |t'| \leq 0.7 \text{ GeV}^2$.
Dashed curves indicate the fitted intensity of a pure Deck process.

Fig. 1

Fig. 2

Fig. 3 a - d)

Fig. 3 e)

Fig. 4