Observation of a New Scalar Meson

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(Received 29 March 1976)

We have observed the production of a new scalar meson of mass 1255 ± 5 MeV and width 79 ± 10 MeV. The meson is observed primarily through the interference of the S-wave and D-wave $K_s{}^0K_s{}^0$ production amplitudes in the reaction $\pi^- p \to nK_s{}^0K_s{}^0$ at 6 and 7 GeV/c. The S-wave amplitude and phase are both observed to have Breit-Wigner behavior. The quantum numbers of the meson are $J^P = 0^+$ and $C = +1$ with $I^G = 1^-$ preferred.

We report the results of an analysis of an experiment studying the reaction $\pi^- p \to nK_s{}^0K_s{}^0$ carried out at the Argonne National Laboratory zero gradient synchrotron utilizing the 1.5-m streamer-chamber facility. Some experimental details have been published previously.[1,2] Briefly, the trigger required an incident beam particle into a 7.5-cm-long liquid-hydrogen target in the streamer chamber, no charged particles emerging from the target, and signals from at least two scintillation counters in a downstream hodoscope. Some 400 000 pictures were taken, approximately 70% at 7 GeV/c and the remainder at 6 GeV/c. These data are combined in this analysis. About 8% of the 400 000 events were of "double-vee" topology and were processed using TVGP and SQUAW. The distribution of the square of the missing mass for the 16 000 events consistent with $K_s{}^0K_s{}^0$ production has a very prominent neutron peak with < 10% background. After appropriate χ^2 cuts and fiducial-volume cuts, we obtain a very clean final simple of 5096 unweighted $nK_s{}^0K_s{}^0$ events.

We have studied our acceptance as a function of the $K_s{}^0K_s{}^0$ effective mass, M_{KK}; the four-momentum transfer from the proton to the neutron, t; and the decay angles in the Gottfried-Jackson frame, $\cos\theta_J$ and φ_{TY}. In all four variables the acceptance is quite uniform, slowly varying, and nowhere extremely low. In Fig. 1 the M_{KK} distribution is shown weighted and unweighted (shaded). The average weight is 2.1 and differs from unity primarily because of target-escape probability. The average $K_s{}^0K_s{}^0$ effective-mass resolution is ±3, ±9, and ±15 MeV at 1050, 1300, and 1600 MeV, respectively. The M_{KK} distribution shows the well-known threshold enhancement, the S^*, and a broad peak in the 1350-MeV mass range from 1200 to 1500 MeV. This broad peak is in a mass region where the $J^P = 2^+$ mesons, the f, $A_2{}^0$, and f', might be expected to contribute.

Figure 2 shows the unnormalized t-channel moments $\langle \mathrm{Re}\,Y_l{}^m\rangle$ as a function of M_{KK} for $|t| < 0.2$ GeV^2. Here $\langle \mathrm{Re}\,Y_l{}^m\rangle = \int W(\Omega)\,\mathrm{Re}\,Y_l{}^m(\Omega)\,d\Omega$, where

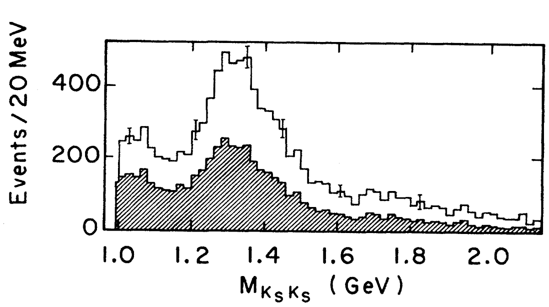

FIG. 1. The $K_s{}^0K_s{}^0$ effective mass distribution for all events weighted (full curve) and unweighted (cross hatched).

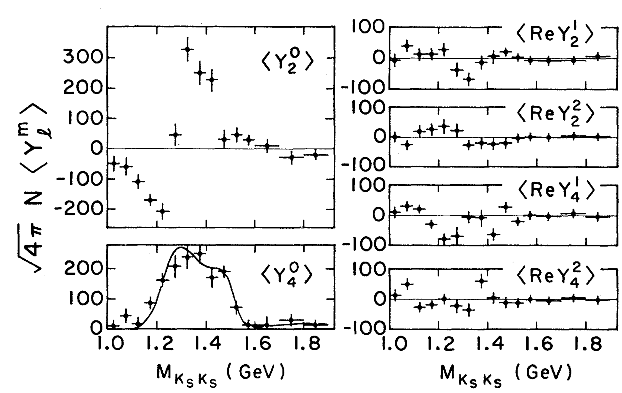

FIG. 2. The unnormalized moments $\langle Y_l{}^m\rangle$ as a function of M_{KK}. The smooth curve on $Y_4{}^0$ is a fit to the data using f-f' interference (see text).

$W(\Omega)$ is the decay angular distribution normalized to unity. The moments were determined by a maximum-likelihood fit to each mass bin. Moments with $l \geq 6$ and $m \geq 3$ were all consistent with zero and were excluded from the final fit. The $\langle Y_4^0 \rangle$ moment, which is dominated by $J^P = 2^+$ $K_s^0 K_s^0$ production, is quite broad and is clearly not explainable solely by f production. The $\langle Y_2^0 \rangle$ moment shows a strong S-D interference pattern. It can be concluded qualitatively that there is significant S wave in the f-mass region, and that the $J^P = 0^+$ and $J^P = 2^+$ production amplitudes are quite coherent.

Our goal in this work is to understand the S-wave amplitude. To this end we must understand the D-wave amplitude, i.e., the $\langle Y_4^0 \rangle$ moment as a function of M_{KK}. A recent analysis[3] of the reaction $\pi^- p \to n K^+ K^-$ at 6 GeV/c has shown the presence of f-f' interference in the $\langle Y_4^0 \rangle$ moment.[4] Using this as a guide, we have fitted[5] our $\langle Y_4^0 \rangle$ distribution by f-f' interference using accepted values for the f mass and width and the f' mass. We varied the f-f' phase, the f' width, and the relative f-f' intensity. The best fit[6] is shown as the curve on the $\langle Y_4^0 \rangle$ distribution in Fig. 2. These results are quite consistent with the results of Pawlicki *et al.*[3] and we feel confident that this is the explanation of the broad $J^P = 2^+$ bump.

In order to extract the S-wave amplitude, we have performed a production-amplitude analysis[7,8] and have written the moments in terms of S, D_0, D_{1+}, D_{1-}, and $\cos(\varphi_S - \varphi_D)$, the magnitudes of the S- and D-wave amplitudes and the phase angle between them, respectively. Here D_{1+} and D_{1-} are linear combinations of the $m = \pm 1$ amplitudes corresponding to natural- and unnatural-parity exchange, respectively. In this analysis we have made the following assumptions: No $l \geq 4$ waves are present; no $m = 2$ helicity states are produced; nucleon spin-flip dominance; and there is phase coherence.

The results of the amplitude analysis are shown in Fig. 3. We note that S and D_0 dominate although D_{1+} and D_{1-} are not zero everwhere. The S-wave intensity is large at threshold (the S^*), decreases, and then goes through a second maximum in the region near 1270 MeV. The shape is very suggestive of an S-wave resonance on a smoothly falling S-wave background.

The fitted phase difference φ_{SD} can be used to extract the S-wave phase if the D-wave phase is known. Since we observe that the D-wave amplitude can be explained in terms of f and f' production, we have used the corresponding D-wave phase to calculate φ_S. In Figs. 4(a) and 4(b) φ_D and φ_S are shown. There are two solutions for φ_S since only $|\varphi_S - \varphi_D|$ is determined. We note that solution 1 has φ_S changing by ~180° in a fairly small range of M_{KK} with a shape quite characteristic of a Breit-Wigner phase variation whereas solution 2 is slowly varying with no obvious structure. The smooth curve shown on solution 1 is a least-squares fit with a Breit-Wigner and yields the resonance parameters $M = 1255 \pm 5$ MeV and $\Gamma = 79 \pm 10$ MeV and a production phase of 110°

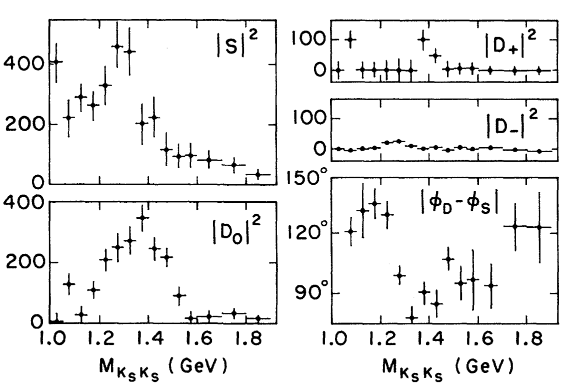

FIG. 3. Fitted parameters of the amplitude analysis (see text) as a function of M_{KK} using data with $|t| < 0.2$ GeV^2.

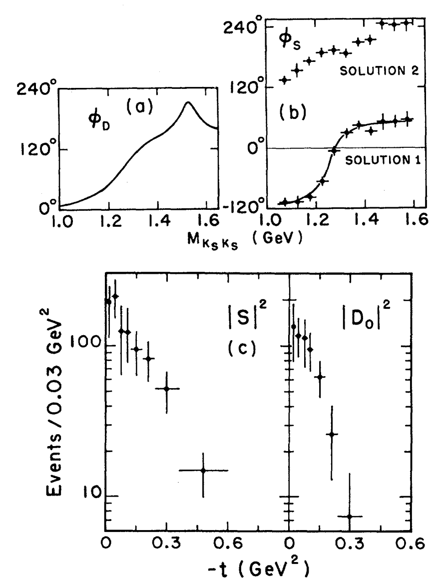

FIG. 4. (a) The D-wave phase, φ_D, from the f-f' fit to $\langle Y_4^0 \rangle$. (b) The S-wave phase obtained from combining the results from the amplitude analysis ($|\varphi_S - \varphi_D|$) with φ_D from (a). Both solutions are shown. The smooth curve is a Breit-Wigner fit to the data. (c) $|S|^2$ and $|D_0|^2$ as a function of t for 1.22 GeV $< M_{KK} <$ 1.32 GeV.

$\pm 4^\circ$ relative to the f^0 production phase. These parameters are consistent with the peak in the S-wave intensity observed in Fig. 3. Thus although we cannot rule out solution 2, the Breit-Wigner phase variation of solution 1 combined with the intensity variation in Fig. 3 impels us to conclude that we have observed the presence of a resonance with $J^P = 0^+$ and $C = +1$.

The S-wave resonance must have $I^G = 0^+$ or 1^- since the $K_s^0 K_s^0$ system must have $G = (-1)^I$. If $I^G = 0^+$, one might expect pion exchange to dominate its production. If $I^G = 1^-$, pion exchange is forbidden. Production of the f meson is known to be dominated by pion exchange and one would expect that if the S-wave resonance were produced by pion exchange, the production amplitudes would either be in phase or 180° out of phase in contrast with the fit of $110^\circ \pm 4^\circ$. This suggests that the S-wave resonance is not produced by pion exchange.

To study the production mechanism further, we have performed an amplitude analysis as a function of t. We show in Fig. 4(c) the resulting fits for $|S|^2$ and $|D_0|^2$ as a function of t for $1.22 < M_{KK} < 1.32$ GeV. The slope of the t distribution for $|D_0|^2$ is 11.9 ± 1.2 GeV^{-2} consistent with one-pion exchange (as expected for the f) but for $|S|^2$ it is 3.7 ± 0.8 GeV^{-2}. (The slopes were fitted over a range of $0.06 < |t| < 0.36$ GeV^2.) This verifies that the S-wave resonance is not dominated by pion exchange[9] and suggests $I^G = 1^-$.

A further argument can be made for the $I^G = 1^-$ assignment. The S-wave resonance must be produced via isovector exchange with unnatural spin parity. Excluding pion exchange, the candidates are B exchange (leading to $I^G = 1^-$) and A_1 exchange (leading to $I^G = 0^+$). It is expected that A_1 exchange[7] would couple dominantly to the nonflip amplitude at the nucleon vertex and thus be incoherent with π exchange which is dominated by spin flip. On the other hand, B exchange couples dominantly to the spin-flip amplitude and is expected to be coherent with pion exchange. Since the S-wave resonance production is coherent with pion exchange, B exchange is favored, again suggesting $I^G = 1^-$. We conclude that the S-wave resonance has the same quantum numbers as the $\delta(970)$, and we therefore refer to it as the δ'.

It has been suggested[10] that the $\delta(970)$ is not a resonance, but an enhancement due to the $K^\pm K^0$ threshold. If this is the case, then the δ' would be the obvious candidate for the $I = 1$ member of the 0^+ nonet of SU(3). It is interesting then that the isovector states of the 0^+ and 2^+ nonets with $C = +1$ (the $q\bar{q}$ p-wave states with $S = 1$) have similar masses. These are the $\delta'(1255)$ and the $A_2(1310)$. This suggests that the $q\bar{q}$ $\vec{L}\cdot\vec{S}$ coupling is small and that the missing 1^+ state (the A_1) might be found near 1300 MeV. Furthermore, it would be logical to conclude that the S^* is a threshold enhancement [like the $\delta(970)$] and that another $J^P I^G = 0^+ 0^+$ state should exist. Candidates for such a state have been reported[11] in the past.

We would like to acknowledge the excellent cooperation of the streamer chamber personnel, the zero gradient synchrotron staff, and the Notre Dame scanning staff. Without their dedicated efforts this work would not have been possible. We are also indebted to R. Erichsen, W. Rickhoff, and A. Horvath for their technical expertise and hard work. We have profited from private conversations with G. Kane, J. Rosner, A. Martin, and A. Pawlicki.

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*On leave 1975–1976 at the University of Nijmegen, Nijmegen, Netherlands.

†Research supported in part by the National Science Foundation.

‡Research supported by the Energy Research and Development Administration.

[1]V. A. Polychronakos *et al.*, Phys. Rev. D 11, 2400 (1975).

[2]N. M. Cason, in Proceedings of the Eleventh Rencontre de Moriond, 1976, edited by J. Tran Thanh Van (to be published), Vol. 1.

[3]A. J. Pawlicki *et al.*, ANL Report No. ANL-HEP-CP-75-50 (to be published), and private communication.

[4]The fact that the $\langle Y_4^0 \rangle$ moment distributions in the K^+K^- and $K_s^0 K_s^0$ data are very similar in shape rules out f-A_2^0 interference as the cause of the broad peak in the 1350-MeV region. That is, there must be a 180° phase difference in the f-A_2^0 interference between K^+K^- and $K_s^0 K_s^0$ which would lead to markedly different shapes for $\langle Y_4^0 \rangle$. See, e.g., H. J. Lipkin, Phys. Rev. 176, 1709 (1968), and W. Beusch *et al.*, Phys. Lett. 60B, 101 (1975).

[5]The Breit-Wigner amplitudes used in this paper are of the form $B = A(\Gamma_{KK})^{1/2}/(M^2 - M_0^2 - iM_0\Gamma_{\rm tot})$. Here A is a real constant, and M_0 is the resonant mass. The partial width $\Gamma_{KK} = \Gamma_0[(qr)^{2l+1}/D_l][(qr)^{2l+1}/D_l]_0^{-1}$, where Γ_0 is a constant, q is the K momentum in the $K_s^0 K_s^0$ rest frame, l is the orbital angular momentum, and the subscript 0 on the last factor indicates that the factor is to be evaluated at the resonant mass. The centrifugal-barrier factors are given by $D_0 = 1$, $D_2 = 9 + 3(qr)^2 + (qr)^4$, where the interaction radius r was chosen to be 3.5 GeV^{-1}. The total width $\Gamma_{\rm tot} = \sum_i \Gamma_i$, where the sum is taken over the partial widths.

[6]The fitted parameters are $\Gamma_{\rm tot}(f') = 92^{+39}_{-22}$ MeV, $\varphi(f') - \varphi(f) = 178^\circ \pm 9^\circ$, and the ratio of the f' intensity to the f intensity is 0.14 ± 0.04. An analysis of the t depen-

dence of $<Y_4^0>$ (not shown) shows that A_2^0 production is very small [see also W. Beusch *et al.*, Phys. Lett. 60B, 101 (1975)] and can be safely ignored in the analysis to follow.

[7]P. Estabrooks *et al.*, in π-π *Scattering—1973*, AIP Conference Proceedings No. 13, edited by P. K. Williams and V. Hagopian (American Institute of Physics, New York, 1973), p. 37.

[8]W. Ochs, Nuovo Cimento 12A, 724 (1972).

[9]A recent experiment (Beusch *et al.*, Ref. 6) studying the reaction $\pi^- p \to nK_S K_S$ at 9 GeV/c finds moments similar to ours but no evidence for an S-wave resonance. A possible explanation of the discrepancy is their assumption of pion exchange in their amplitude analysis.

[10]S. Flatté, in Proceedings of the Eleventh Rencontre de Moriond, 1976, edited by J. Tran Thanh Van (to be published), Vol. 1.

[11]J. T. Carroll *et al.*, Phys. Rev. Lett. 28, 318 (1972). See also Ref. 7.

Observation of the Infrared Spectrum of the Hydrogen Molecular Ion HD^+

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(Received 13 May 1976)

Published without review at the request of Peter Franken under policy announced 26 April 1976

The vibration-rotational spectrum of the hydrogen molecular ion HD^+ has been observed by means of a new ion-beam laser-resonance method employing Doppler-effect tuning and collisional detection. Six transition-frequency groups between 1642 and 1869 cm^{-1}, exhibiting partially resolved hyperfine structure, have been measured to ± 1 ppm. The accuracy exceeds that of present theoretical calculations of HD^+ energy levels.

The hydrogen molecular ion is the simplest molecule in nature, consisting of two nuclei and a single electron. It has been the subject of numerous theoretical treatments, which begin with the solutions of the nonrelativistic, one-particle, two-center problem, one of the few separable problems in quantum mechanics.[1] In the physical molecule, the constituents vibrate and rotate about the center of mass. Tables of adiabatic vibration-rotational energy levels in the $1s\sigma^2\Sigma_g^+$ electronic ground state (including nuclear-motion terms diagonal in the electronic basis) have been prepared most recently by Hunter, Yau, and Pritchard.[2] Nonadiabatic (nonrelativistically exact) calculations have also been made for a few low-lying levels.[3,4] In the electronic ground state, a heteronuclear isotope of the ion will interact strongly with optical radiation fields because its mass asymmetry and net charge lead to a substantial electric-dipole transition moment. A homonuclear ion will interact weakly via its electric-quadrupole transition moment.[5]

Spectroscopically, however, the molecule has remained elusive. While spectra of most common molecules have been measured with accuracies of a few parts per million, the optical absorption or emission spectrum of the hydrogen molecular ion has not been seen heretofore. Past searches for the spectrum have been frustrated by the gas-phase reaction $H_2^+ + H_2 \to H_3^+ + H$, which proceeds rapidly for all isotopes in thermal plasmas of appreciable density, keeping H_2^+ concentrations too low for conventional spectroscopic techniques. At present the most accurate observational information on energy levels is derived from vacuum-ultraviolet absorption studies[6] of Rydberg-series limits in the isotopes of molecular hydrogen with uncertainties of a few parts per ten thousand. At this level the calculations and data are in agreement. Experimental data of greater accuracy would make it possible to test a more realistic molecular model incorporating a relativistic wave equation and the effects of quantum electrodynamics.

We have observed infrared transitions between electronic-ground-state vibration-rotational levels of the heteronuclear hydrogen molecular ion HD^+, using a new ion-beam laser-resonance method. A schematic diagram of the experimental apparatus is shown in Fig. 1. In a region of constant electrostatic potential an ion beam of several keV energy crosses at a small angle (≈ 11 mrad) the beam from an infrared molecular laser. The accelerating potential is adjusted to Doppler shift an ion transition into resonance with a nearby laser line. The ions then pass through a gas target where they are partially neutralized by charge exchange (and, to a lesser extent, dissociated and scattered), and are collected in a Faraday cup.