Scalar Mesons in $\pi\pi$ and $\bar{K}K$: Results of a Unitary Amplitude Analysis

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The $\pi\pi \to \bar{K}K$ S wave has been extracted from an amplitude analysis of $\bar{K}K$ production. With use of unitarity constraints, evidence has been found for a resonance in $\pi\pi \to \bar{K}K$ at 1425 ± 15 MeV/c^2 having a width 160 ± 30 MeV/c^2; this state is a likely candidate for the $Q\bar{Q}$, $J^{PC} = 0^{++}$ nonet. It is shown that the $S^*(980)$, which is a background to this resonance, must be a very broad effect and is likely a $\bar{K}K$ virtual bound state.

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The spectrum of scalar mesons has never been clearly resolved, and theoretical expectations of two-quark, four-quark, and gluonium states in this sector make the experimental study of $J^{PC} = 0^{++}$ states a central issue in light-quark spectroscopy. In this paper we present evidence for an $I = 0$ scalar-meson resonance in the $\pi\pi \to \bar{K}K$ S-wave amplitude, with mass 1425 ± 15 MeV/c^2 and width 160 ± 30 MeV/c^2. The measured $\pi\pi \to \pi\pi$ elastic S-wave phase shifts suggest that this state couples mainly to $\pi\pi$, and we refer to it henceforth as $\epsilon(1425)$. As a by-product of our study, we show that the $S^*(980)$ cannot consistently be described as a narrow resonance, but is either a very broad state or a $\bar{K}K$ virtual bound state. The key ingredients in our analysis are, first, the behavior of the $\pi\pi \to \bar{K}K$ S-wave phase as determined from our experiment, and second, the unitarity constraints on the coupled-channels S matrix.

Historically, Morgan's[1] classification of scalar mesons involved very broad κ (≈ 1200) and ϵ (≈ 1300) states together with narrower ($\Gamma \approx 200$ MeV) $\delta(980)$ and $S^*(980)$ resonances. The mass spectrum and mixing angle seemed unnatural, leading Jaffe[2] to suggest that some of these objects were, in fact, four-quark states with very broad widths, and that the genuine $Q\bar{Q}$ nonet should appear in the 1200–1600-MeV/c^2 range. The subsequent clarification of the $I = \frac{1}{2}$ S-wave $K\pi \to K\pi$ scattering amplitude by Estabrooks *et al.*[3] lent support to Jaffe's model. The $K\pi$ phase shifts show a rapid advance above 1400 MeV/c^2, suggesting a relatively narrow κ (≈ 1500) resonance superimposed on a broad background. Similarly, the observation of a peak in the $\bar{K}K$ S-wave production cross section[4,5] near 1300 MeV/c^2 suggested a nonstrange companion to the $\kappa(1500)$, but the correlation between phase and intensity seemed inconsistent with a simple resonance. In a preliminary analysis,[5] we showed that this enhancement occurred mainly in the $I = 0$ S wave. In this paper we explain the correlation between phase and intensity in terms of the $S^*(980)$ and the $\epsilon(1425)$.

We have extracted the $\pi\pi \to \bar{K}K$ amplitudes from an analysis of the reactions $\pi^- p \to K^- K^+ n$ and $\pi^+ n \to K^- K^+ p$ (160 000 events) at 6 GeV/c, measured with the Argonne National Laboratory effective-mass spectrometer.[6] The details of this analysis are reported elsewhere.[7] To summarize the work of Ref. 7, we have used spin-coherence assumptions valid for π-exchange dominance to extract the unnatural–parity-exchange (UPE) amplitudes for production of S, P, and D $\bar{K}K$ waves with $I = 0$ and 1. To resolve discrete ambiguities, we have chosen a solution which uniquely satisfies the following physical requirements: (1) The charge-symmetric reactions $\pi^+ n \to K^- K^+ p$ and $\pi^- p \to K_S K_S n$ (from Ref. 4) have the same mass and t dependence in the S and D waves; (2) the S waves in $\pi^- p \to K^- K^+ n$ and $\pi^+ n \to K^- K^+ p$ extrapolate to the same values at the pion pole; (3) the t dependences (e^{at}, with $a \approx 11$) of the $I = 0$ S and D waves and $I = 1$ P wave are consistent with π exchange, while the $I = 1$ S and D waves and $I = 0$ P waves show behavior (e^{at}, with $a \approx 3.5$) similar to that in B-exchange reactions (e.g., UPE in $\pi^- p \to \omega n$ and $\pi^- p \to A_2{}^0 n$); (4) the P waves are consistent in magnitude and phase with the expected tails of the $\rho(770)$ and $\omega(783)$ resonances. We have used the assumed Breit-Wigner behavior of both the P and D waves to constrain the overall S-wave phases, and we have repeated the analysis in two t intervals ($-t < 0.08$ GeV^2 and $0.08 \leq -t < 0.20$ GeV^2) with consistent results. The following discussion is based on the data from the $-t < 0.08$ GeV^2 interval. Finally, we have checked for stability against the spin-coherence assumption by introducing a resonant $I = 1$ S wave produced by Z exchange, as proposed by Martin and Ozmutlu[8] in an analysis of the reaction $\pi^- p \to K^- K^0 p$; our results for the π- and B-exchange

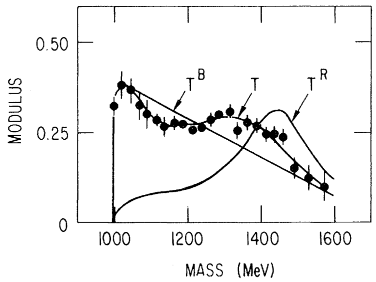

FIG. 1. Modulus of the S-wave $\pi\pi \to \bar{K}K$ scattering amplitude $T(\pi\pi \to \bar{K}K)$. The curves show the moduli of the S^* background (T^B) and the $\epsilon(1425)$ resonance (T^R), from decomposition described in the text.

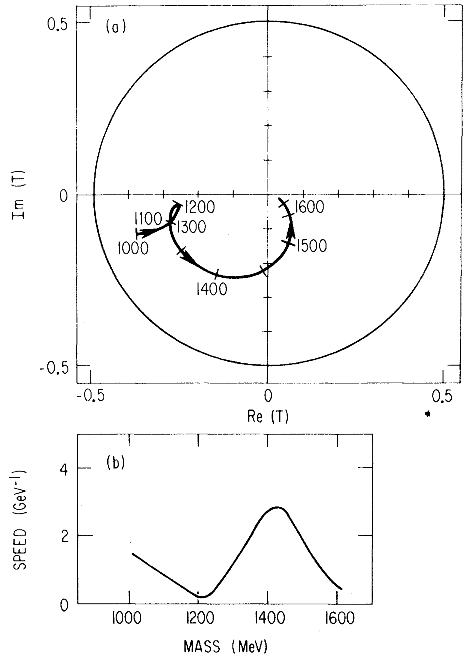

FIG. 2. (a) Argand plot for $\pi\pi \to \bar{K}K$ from a smooth polynomial parametrization. (b) Speed, as deduced from the Argand plot in (a).

S waves are insensitive to the inclusion of such an effect.

The modulus of the $I=0$, $\pi\pi \to \bar{K}K$ S wave (see Fig. 1) shows an S^*-associated peak near threshold and a broad shoulder centered at 1300 MeV/c^2. Using a polynomial parametrization, we have obtained the smoothed Argand plot shown in Fig. 2(a). The speed, $|dT(\pi\pi \to \bar{K}K)/dM|$ in Fig. 2(b), shows a peak at 1425 MeV/c^2 with a width of ≈ 160 MeV/c^2 (for constant background, the speed associated with a resonance should vary with mass like a Breit-Wigner intensity). Note that the large S^*-related background amplitude, which has a $\approx 190°$ phase, causes the $\epsilon(1425)$ to appear upside down on the Argand plot.

The critical untested assumption in our analysis is that $\pi\pi$ and $\bar{K}K$ are the dominant channels for the $I=0$ S wave, and that other channels ($\rho\rho$, $\pi A_1, \ldots$) are unimportant below 1500 MeV/c^2. For the two-channel case, the amplitude for $\pi\pi \to \bar{K}K$ has the form

$$T(\pi\pi \to \bar{K}K) = \tfrac{1}{2}(1-\eta^2)^{1/2}\exp[i(\delta_\pi + \delta_K)], \qquad (1)$$

where δ_π and δ_K are the elastic $\pi\pi$ and $\bar{K}K$ phase shifts. If the two-channel T matrix is decomposed into a Breit-Wigner resonance plus unitary background, $T = T^R + T^B$, then unitarity provides the important constraint[9]

$$\varphi(\pi\pi \to \bar{K}K) = \delta_\pi{}^B + \delta_K{}^B + \delta^R, \qquad (2)$$

where $\varphi(\pi\pi \to \bar{K}K)$ is the phase of $T(\pi\pi \to \bar{K}K)$, $\delta_{\pi,K}{}^B$ are the elastic phase shifts that describe T^B, and $\delta^R = \delta_\pi{}^R + \delta_K{}^R$ is the Breit-Wigner phase $[=\arg(M_R - M + i\Gamma/2)]$ associated with T^R. Note that neither the background elasticity (η_B) nor the relative couplings of the resonance enter Eq. (2). Thus, in the absence of other channels, we expect $\varphi(\pi\pi \to \bar{K}K)$ to show a $\sim 180°$ phase advance for each resonance, superimposed on a smooth background phase.

Figure 3(a) shows smooth interpolations of the "A" and "B" $\pi\pi$ elastic phase shifts found by Estabrooks and Martin,[10] together with solution β of Pennington and Martin.[11] The latter solution most closely matches the "unique" $\pi\pi$ amplitudes reported by Becker *et al.*,[12] in particular the rapid falloff of the $\pi\pi \to \pi\pi$ S-wave magnitude above 1400 MeV/c^2. In the region from 1200 to 1600 MeV/c^2, both δ_π in Fig. 3(a) and $\varphi(\pi\pi \to \bar{K}K)$ in Fig. 3(b) show similar phase advances of $\approx 100°$; the $\bar{K}K$ elastic phase shift, obtained by subtracting δ_π from $\varphi(\pi\pi \to \bar{K}K)$, is stationary in this region [Fig. 3(c)]. Thus we conclude that the $\epsilon(1425)$ couples mainly to $\pi\pi$ and has a negligible effect on δ_K; it causes essentially the same phase advance in δ_π and in $\varphi(\pi\pi \to \bar{K}K)$, as prescribed by Eq. (2). The curve in Fig. 3(b) is based on a fit to $\varphi(\pi\pi \to \bar{K}K)$ in terms of the $\epsilon(1425)$ mass and width and the background phase shifts $\delta_\pi{}^B$ and $\delta_K{}^B$; the dashed curve in Fig. 3(a) shows the prediction for δ_π from this fit.

The effects of the $S^*(980)$ can be seen in the region below 1300 MeV/c^2. Near $\bar{K}K$ threshold, δ_π

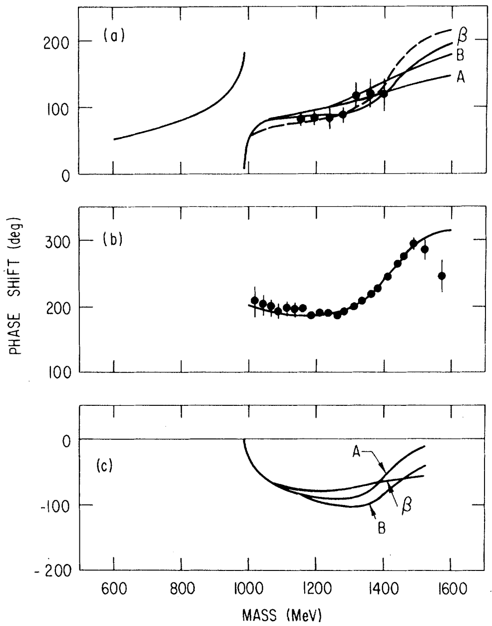

FIG. 3. (a) Smooth interpolations of measured $\pi\pi$ phase shifts (modulo 180°) from Refs. 10 (curves A and B), 11 (curve β), and 12 (data points); the dashed curve shows δ_π predicted from our fit to $\varphi(\pi\pi\to\bar{K}K)$. (b) Measured $\varphi(\pi\pi\to\bar{K}K)$ from our amplitude analysis with fitted curve. (c) $\bar{K}K\to\bar{K}K$ elastic phase shifts corresponding to the various δ_π solutions.

increases rapidly by 180°, while δ_K decreases to $\approx -80°$, leaving $\varphi(\pi\pi\to\bar{K}K)$ essentially stationary below 1300 MeV/c^2. The rapid variations in δ_π and δ_K above $\bar{K}K$ threshold can be attributed to a rapid increase in the ratio $\Gamma(S^*\to\bar{K}K)/\Gamma(S^*\to\pi\pi)$, which causes the $\bar{K}K\to\bar{K}K$ elastic amplitude to move quickly to the top of its Argand plot. The fact that δ_K does not return to 0°, and the fact that $\varphi(\pi\pi\to\bar{K}K)$ does not show the Breit-Wigner phase advance expected from Eq. (2), both argue that the S^* total width [given mainly by $\Gamma(S^*\to\bar{K}K)$] must become very broad above $\bar{K}K$ threshold. We have parametrized the S^* effect as a virtual $\bar{K}K$ bound state (see Ref. 1) to obtain the description of δ_π and $\varphi(\pi\pi\to\bar{K}K)$ shown by the curves in Figs. 3(a) and 3(b).

While the phase behavior gives direct information on the mass and width of the S^* and $\epsilon(1425)$, the modulus of the $\pi\pi\to\bar{K}K$ amplitude is a delicate convolution of the S^* and the $\epsilon(1425)$. Regarding the S^* as a background to the $\epsilon(1425)$ resonance, we have used the formalism of Coulter[13] to derive the following unitarity constraints on the amplitude $T=T^B+T^R$:

$$|T(\pi\pi\to\bar{K}K)| = (x_\pi x_K)^{1/2}|\sin(\delta^R+\theta)|, \qquad (3a)$$

$$|T^B(\pi\pi\to\bar{K}K)| = (x_\pi x_K)^{1/2}\sin\theta, \qquad (3b)$$

$$|T^R(\pi\pi\to\bar{K}K)| = (x_\pi x_K)^{1/2}\sin(\delta^R), \qquad (3c)$$

where $x_{\pi,K}$ are the $\epsilon(1425)$ branching fractions $\Gamma_{\pi,K}^{\epsilon}/\Gamma^{\epsilon}$, and θ is a unitarity phase, $0\le\theta\le\pi$. The relative $\pi\pi:\bar{K}K$ coupling sign for $\epsilon(1425)$ is related to the quadrant of θ; $\theta<\pi/2$ ($\theta>\pi/2$) corresponds to a + (−) sign. Thus, for positive coupling, any background in $\pi\pi\to\bar{K}K$ necessarily shifts the $\epsilon(1425)$ peak in $|T(\pi\pi\to\bar{K}K)|$ to a lower mass. Furthermore, if $|T^B|$ falls with mass, then the phase $\delta^R+\theta$ tends to remain stationary, broadening the resonance peak. Although our analysis does not determine $|T^B|$ uniquely, a typical decomposition into resonance and background is shown in Fig. 1, where the coupling $(x_\pi x_K)^{1/2}$ varies smoothly with mass. The 1300-MeV/c^2 enhancement is seen to be a distortion of the $\epsilon(1425)$, for which we obtain a possible range of couplings $0.28\le(x_\pi x_K)^{1/2}\le 0.40$, with positive coupling sign.

In conclusion, by taking proper account of unitarity constraints, we have shown that the $\pi\pi\to\bar{K}K$ amplitude behaves like a superposition of a broad S^* background and the $\epsilon(1425)$ resonance. The 1300-MeV/c^2 enhancement in $\bar{K}K$ is a convolution of these two effects. The $\epsilon(1425)$ shows clear Breit-Wigner behavior with $\Gamma=160\pm 30$ MeV/c^2, whereas the S^* does not. Thus we conjecture that the $\epsilon(1425)$, not the $S^*(980)$, is a likely companion of $\kappa(1500)$ in a $Q\bar{Q}$ scalar nonet. The coupling, $0.28\le(x_\pi x_K)^{1/2}\le 0.40$, may be compared with the value 0.40 expected for an ideally mixed $u\bar{u}+d\bar{d}$ $I=0$ state. Better data on the $\pi\pi$ phase shifts would aid in confirming our analysis, as would identification of additional $I=1$ ($u\bar{d}$) and $I=0$ ($s\bar{s}$) states in the 1300–1600-MeV/c^2 region.

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[1]D. Morgan, Phys. Lett. 51B, 71 (1974).
[2]R. L. Jaffe, Phys. Rev. D 15, 267 (1977).
[3]P. Estabrooks *et al.*, Nucl. Phys. B133, 490 (1978).
[4]N. M. Cason *et al.*, Phys. Rev. Lett. 36, 1485 (1976).
[5]A. J. Pawlicki *et al.*, Phys. Rev. Lett. 37, 1666

(1976).
[6]A. J. Pawlicki *et al.*, Phys. Rev. D 15, 3196 (1977).
[7]D. Cohen *et al.*, Phys. Rev. D (to be published).
[8]A. D. Martin and E. N. Ozmutlu, Nucl. Phys. B158, 520 (1979).
[9]R. H. Dalitz and R. G. Moorhouse, Proc. Roy. Soc., Ser. A 318, 279 (1970).
[10]P. Estabrooks and A. D. Martin, Nucl. Phys. B95, 322 (1975).
[11]A. D. Martin and M. R. Pennington, Ann. Phys. (N.Y.) 114, 1 (1978).
[12]H. Becker *et al.*, Nucl. Phys. B151, 46 (1979); the phase shifts shown in Fig. 3(a) are derived from an average of the g_s and h_s amplitude phases reported by them.
[13]P. W. Coulter, Phys. Rev. Lett. 29, 450 (1972), and Phys. Rev. D 7, 7 (1973). Coulter's formalism implies Eq. (2) as well as Eq. (3).

Dynamic Influence of Valence Neutrons upon the Complete Fusion of Massive Nuclei

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Excitation functions for complete fusion of $^{58}Ni+^{58}Ni$, $^{58}Ni+^{64}Ni$, and $^{64}Ni+^{64}Ni$ have been determined over a range of energies from just above to well below the fusion barrier. The response of these excitation functions to the addition of valence neutrons is found to be surprisingly complex. We suggest that at least part of the observed variations may be due to dynamic, single-particle effects.

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Measurements of cross sections for complete fusion at near-barrier and subbarrier energies provide basic information on the large-scale behavior of nuclear matter and on the influence upon this behavior of the underlying nuclear structure. In addition to providing data for testing various interaction potentials and probing (in principle) the nuclear potential at the inner side of the interaction barrier, such measurements may provide insight into a number of predicted static and dynamic aspects. Theoretical predictions which have been made include the occurrence of Coulomb distortions, rotations, and the excitation of vibrational states,[1-3] of quantal oscillations,[4] and the influence of nuclear stiffness[5] and static deformations.[6] Recent experimental investigations,[7-9] involving ^{16}O to ^{40}Ca projectiles, have revealed the presence of substantial subbarrier penetration. These data have been used to test for the predicted influence of static deformations with suggestive, although somewhat inconclusive, results.[10,11]

In this Letter we present results of measurements of complete-fusion excitation functions for $^{58}Ni+^{58}Ni$, $^{58}Ni+^{64}Ni$, and $^{64}Ni+^{64}Ni$ at near-barrier and subbarrier energies. These Ni systems involve more massive projectiles than used previously and comprise a triad of massive, nearly closed-shell symmetric, target-projectile combinations. We find that the response of the Ni-Ni excitation functions to the addition of valence neutrons is complex, more so than observed in systems involving lighter projectiles. We then suggest that at least part of the observed variations may be due to dynamic, single-particle effects.

In order to determine the excitation functions we measured evaporation residue differential cross sections using the Massachusetts Institute of Technology–Brookhaven National Laboratory (MIT-BNL) velocity selector together with a gas ΔE-E telescope. The use of a velocity selector[12] makes possible the high-precision, near-barrier and subbarrier measurements which cannot be made by systems which are limited by the intense elastic scattering from going to sufficiently forward scattering angles. The experiments were performed using 187–220-MeV ^{58}Ni and 171–215-MeV ^{64}Ni beams provided by the BNL Tandem Van de Graaff Facility to bombard isotopically enriched 70–225-$\mu g/cm^2$ ^{58}Ni and ^{64}Ni targets.

Two silicon surface-barrier detectors placed at 22° angles to the beam axis were used for beam monitoring and normalization. The velocity selector system consisted of a quadrupole doublet, an electrostatic deflector, the velocity selector proper, and a second quadrupole doublet. The gas ΔE-E telescope was placed at the image of the second quadrupole. The ΔE section consisted of a proportional chamber containing isobutane at 20 mm Hg and the E counter was a 450

