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[1]H. F. Weaver, P. Baker, and R. E. Hills, to be published.

[2]D. D. Thornton and W. J. Welch, to be published.

[3]D. R. W. Williams, presented at URSI-IEEE Spring Meeting, Washington, D. C. 20-23 April, 1965 (unpublished).

[4]Microwave Spectral Tables (National Bureau of Standards, Washington, D.C., 1968), Vol. V.

[5]C. H. Townes, in the Fourth International Astronomical Union Symposium, Manchester, England, 1955, edited by H. C. Van de Hulst (Cambridge University Press, Cambridge, 1957), Paper 16.

[6]A. E. Potter and B. Del Duca, Icarus 3, 103 (1964).

EVIDENCE FOR THE $K_1^0K_1^0$ ENHANCEMENT NEAR THRESHOLD PRODUCED BY K^-N INTERACTIONS*

Jean Alitti,† Virgil E. Barnes, David J. Crennell, Enzo Flaminio, Marvin Goldberg,‡ Uri Karshon,§ Kwan Wu Lai, Wesley J. Metzger,‖ John S. O'Neall, Nicholas P. Samios, J. Michael Scarr, and Thomas G. Schumann**
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

A $J^{PC}=0^{++}$ $K_1^0K_1^0$ enhancement at a mass of 1030 ± 10 MeV with a width of 45_{-15}^{+35} MeV is observed in $\bar{K}N$ interactions. An s-wave resonance interpretation of this enhancement is favored over an s-wave scattering length effect. Within experimental uncertainties, we associate this enhancement with the S^* observed in π^-p interactions.

The experimental evidence for an isosinglet, scalar $K_1^0K_1^0$ enhancement ($I^G=0^+$, $J^P=0^+$) comes mainly from a study of the reaction $\pi^-p \to K_1^0K_1^0n$ at pion momenta from 2 to 12 GeV/c.[1] Because the enhancement is near the $K\bar{K}$ threshold the available data can be interpreted either in terms of an s-wave resonance or a simple s-wave complex scattering length.[2] The resonance interpretation, namely the S^* with mass $M=1069\pm10$ MeV and width $\Gamma=72\pm14$ MeV, is favored by the experiments with incident pions of 5, 6, 7, and 12 GeV/c,[3] whereas the scattering-length fit is favored by the experiment at 2.0 GeV/c.[4] In some cases, such as the experiments at 4 and 5 GeV/c, either interpretation can be used to describe the data.[5] In addition, an $I=1$ $K\bar{K}$ enhancement near threshold, $\pi_N(1016$ MeV), has been observed in the reaction $\bar{p}p \to K^\pm K_1^0\pi^\mp$ at rest.[6] This effect has been related to the $\delta^\pm(975)$ boson resonance[7] below the $K\bar{K}$ threshold.[8]

Data for this study come from a number of exposures of the Brookhaven National Laboratory (BNL) 80-in. bubble chamber filled separately with liquid hydrogen and deuterium to separated beams of K^- mesons at 3.6, 3.9, 4.65, and 5.0 GeV/c. A further breakdown concerning the exposures is shown in Table I.

The reaction of interest in this study was $K^-N \to K_1^0K_1^0$(MM), where N was either a proton or neutron and the missing mass (MM) was equal to or greater than that of the Λ^0 hyperon.[9] The main requirement was that both K_1^0's decay in the chamber via their visible decay modes $K_1^0 \to \pi^+\pi^-$. The criteria for the identification of the K_1^0 were that: (1) the K_1^0 decay make a satisfactory three-constraint fit to the production vertex, this being defined by a $\chi^2 \le 12$; (2) the ionization of the π^+ and π^- from the decaying K_1^0 be consistent with that expected from the kinematic fit; and (3) in the case of a Λ^0, K^0 ambiguity, the K^0 interpretation be omitted from the sample[10] because Λ^0's can often be fitted as K_1^0's but the opposite is not often the case.

In Fig. 1(a) is plotted the $K_1^0K_1^0$ mass distribution for this sample of 568 events. Marked enhancements are evident near the $K\bar{K}$ threshold (1030 MeV) and at the well-known f^* resonance (1515 MeV). These regions are indicated in the figure. The cross-hatched events in Fig. 1(a)

Table I. A detailed breakdown of the exposures of the BNL 80-in. liquid-filled bubble chamber to separated beams of K^- mesons.

Beam momentum	Liquid	Events/μb nucleon
3.6	Deuterium	10
3.9	Deuterium	40
3.9	Hydrogen	10
4.65	Hydrogen	15
5.0	Hydrogen	5
Total		80

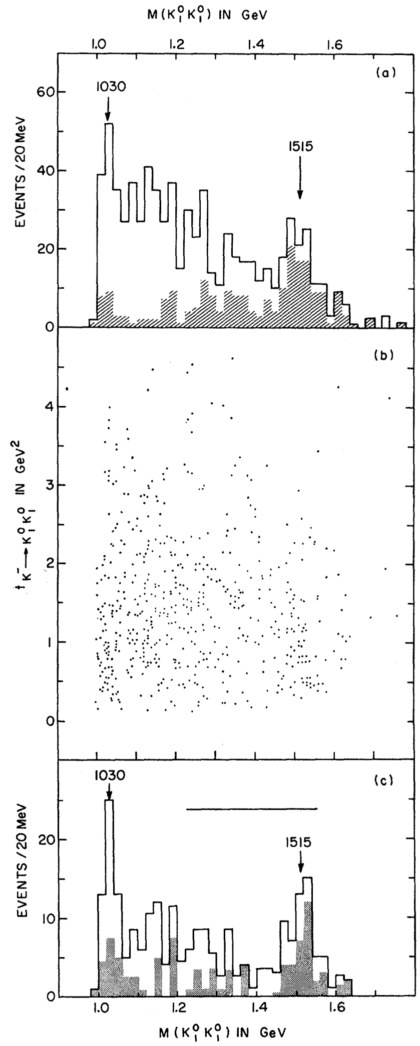

FIG. 1. (a) Total $K_1{}^0K_1{}^0$ mass spectrum. The cross-hatched events correspond to the quasi–three-particle final states. See text for details. (b) Chew-Low plot of $K_1{}^0K_1{}^0$ mass versus $t_{K^-\to K_1{}^0K_1{}^0}$. (c) $K_1{}^0K_1{}^0$ mass spectrum for events with $t_{K^-\to K_1{}^0K_1{}^0} \leq 1.0$ GeV^2. Shaded events are those which have a visible Λ decay in addition to the two visible $K_1{}^0$'s.

correspond to the reaction $K^-N\to K_1{}^0K_1{}^0Y$, where Y denotes a Λ^0, Σ^0, or $Y_1{}^*(1385)$. It is clear that the 1030 enhancement is produced mainly in the multiparticle final states, whereas production of the f^* occurs mostly in quasi–two-body final states. Figure 1(b) is the relevant Chew-Low plot for these reactions. Here the $(K_1{}^0K_1{}^0)$ effective mass is plotted versus the square of the four-momentum transfer between the incident K^- and the $K_1{}^0K_1{}^0$ system $(t_{K^-\to K_1{}^0K_1{}^0})$. It is evident from the Chew-Low plot that there is very little or no production of this 1030-MeV enhancement[11] for $t_{K^-\to K_1{}^0K_1{}^0} > 1$ GeV^2. In order to enhance the peripheral contribution we have replotted the $(K_1{}^0K_1{}^0)$ mass spectrum for the sample of events with $t_{K^-\to K_1{}^0K_1{}^0} \leq 1$ GeV^2, as shown in Fig. 1(c). Two multi-standard-deviation effects are evident at masses of 1030 and 1515 MeV. Only this purer sample of events is considered for further purposes of this study. An s-wave Breit-Wigner resonance fit to the lower peak gives a mass value of $M = 1030 \pm 10$ MeV and a full width $\Gamma = 45^{+35}_{-15}$ MeV.

Several alternative explanations for this 1030-MeV enhancement were investigated. The foremost was the possibility of φ meson production in the $K_1{}^0K_2{}^0$ mode with the subsequent transformation of K_2 into K_1 via the regeneration process $(K_2{}^0N\to K_1{}^0N)$. This possibility was ruled out by the following procedures: (a) All events with $M(K_1K_1) < 1100$ MeV were examined visually for any possible interactions along the $K_1{}^0$ flight path. No such interactions have been observed. (b) Assuming that all the $K_1{}^0K_1{}^0$ events in the 1030-MeV region were due to the regeneration process along the direction of the K_2 flight path which produced no visible or kinematically detectable nucleon, we estimated a lower limit for the φ production cross section in the reactions $K^-N\to\varphi+$others to be $\gtrsim 100$ mb.[12] This is clearly not possible, since the known total cross section of the K^-N interaction is less than 30 mb. In order to determine whether the K_1K_1 enhancement could have been produced by π^-N interactions from any π^- beam contamination,[13] the (K_1K_1) effective mass spectrum from three-V^0 events, namely $K_1{}^0K_1{}^0\Lambda^0(+\pi$'s), which cannot be easily induced by pions, is shown in the shaded area of Fig. 1(c). The 1030 enhancement is clearly evident. We therefore conclude that the low-mass enhancement is a $K_1{}^0K_1{}^0$ effect originating mainly in K^-N interactions.

We now turn to an examination of the quantum numbers of this enhancement. The $K_1{}^0K_1{}^0$ signature restricts the spin, parity, and charge-conjugation quantum numbers to $J^{PC} = 0^{++}$, 2^{++}, 4^{++}, etc. Since the $f^*(1515)$ is also observed, it is used for a comparison; its spin and parity are known to be 2^+.[14] In Figs. 2(a)-2(d), we plotted the decay angular distributions, namely the Jackson and Treiman-Yang angles, for both the 1030-MeV and f^* mass regions. Within the accuracy permitted by the limited statistics, the angular distributions in the 1030 enhancement region are consistent with isotropy, to be contrasted to the strong anisotropy in the Jackson angle for the f^*. This evidence, coupled with the low available Q

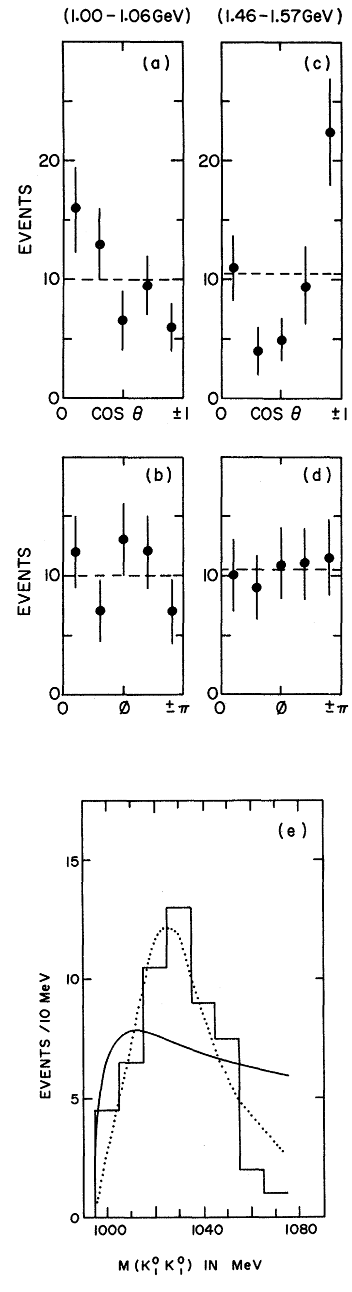

FIG. 2. Distributions of cosine of polar angle folded about $\cos\theta = 0$ are given for (a) the 1030-MeV and (c) $f^*(1515)$ mass regions. Distributions of Treiman-Yang angle folded about $\varphi = 0$ are given for (b) the 1030-MeV and (d) $f^*(1515)$ mass regions. (e) A section of the $K_1^0K_1^0$ mass spectrum with $t_{K^- \to K_1^0K_1^0} \leq 1.0$ GeV^2. The dotted curve is the best fit to the data with an s-wave resonance; the solid curve is the best fit with an s-wave complex-scattering-length effect.

value (40 MeV), favors a $J^{PC} = 0^{++}$ assignment for this enhancement. Experimental difficulties in the identification of charged K-meson tracks in multiparticle final states preclude an isospin (therefore G parity) determination for this enhancement. However, we have searched all possible charged $K\bar{K}$ systems and found no significant excess of events near the threshold (not shown). This observation may suggest the isospin-zero assignment (and therefore $G = +$) for this enhancement.

We have fitted the data with a simple s-wave resonance using two extreme assumptions for the total width of this enhancement (Γ_T), namely $\Gamma_T = \Gamma_{K\bar{K}}$ or $\Gamma_{\pi\pi}$.[15] We find little resulting change in the mass and width. This is allowed for in the errors quoted below. Figure 2(e) shows a section of the $K_1^0K_1^0$ mass spectrum, the resonance fit being shown as the dotted curve with $\Gamma_T = \Gamma_{K\bar{K}}$. The mass and width values obtained are 1030 ± 10 MeV and 45^{+35}_{-15} MeV, respectively, the indicated fit having a $\chi^2 = 4.6$ for six degrees of freedom (60% probability). These values are to be compared with $M = 1069 \pm 10$ MeV and $\Gamma = 72 \pm 14$ MeV obtained for the S^*. We have also tried to fit the data with a simple complex s-wave[16] scattering length ($|a| + ib$) and have obtained a best fit for $|a| = 2.3^{+1.0}_{-0.7}$ F and $b = 0^{+1.8}_{-0}$ F with $\chi^2 = 15$ for six degrees of freedom (2% probability) as shown in the solid curve in Fig. 2(e). It is evident that the best scattering-length fit cannot reproduce the spectrum near the threshold. On the other hand the resonance interpretation gives an excellent fit to the data.

In summary, we have observed a $J^{PC} = 0^{++}$ $K_1^0K_1^0$ enhancement at a mass of 1030 ± 10 MeV and a width of 40^{+35}_{-15} MeV produced in K^-N interactions. The resonance interpretation for this enhancement is favored over a scattering-length interpretation. To the extent that the simple scattering-length procedures carried out are valid, the data presented here give strong support of the existence of a $J^{PC} = 0^{++}$ boson resonance at a mass of 1030 ± 10 MeV. We associate this resonance with the $S^*(1069)$, since both enhancements have the same J^{PC} and, within errors, similar mass values.

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†Present address: Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, Seine et Oise, France.

‡Permanent address: Syracuse University, Syracuse, N. Y.

§On leave of absence from Weizmann Institute of Science, Rehovoth, Israel.

‖Present address: Ecole Polytechnique, Paris, France.

**Permanent address: The City College of the City University of New York, New York, N. Y.

[1]For a recent review on this subject, see K. W. Lai, in Proceedings of an Informal Meeting on Experimental Meson Spectroscopy, Philadelphia, April, 1968 (to be published).

[2]R. H. Dalitz, Rev. Mod. Phys. 33, 477 (1962).

[3]D. J. Crennell, G. R. Kalbfleisch, K. W. Lai, J. M. Scarr, T. G. Schumann, I. O. Skillicorn, and M. S. Webster, Phys. Rev. Letters 16, 1025 (1966); W. Beusch, W. F. Fischer, B. Gobbi, M. Pepin, E. Polgar, P. Astbury, G. Branti, G. Finocchiaro, J. C. Lassalle, A. Michelini, K. W. Terwilliger, D. Websdale, and C. M. West, Phys. Letters 25B, 357 (1967).

[4]R. I. Hess, O. I. Dahl, L. M. Hardy, J. Kirz, and D. H. Miller, Phys. Rev. Letters 17, 1109 (1966); R. J. Hess, thesis, University of California Radiation Laboratory Report No. UCRL-16832, 1966 (unpublished).

[5]T. F. Hoang, D. P. Eartly, J. J. Phelan, A. Roberts, C. L. Sandler, S. Bernstein, S. Margulies, D. W. McLeod, T. H. Groves, N. N. Biswas, N. M. Cason, V. P. Kenney, J. M. Marraffino, J. T. McGahan, J. A. Poirier, and W. D. Shepard, Phys. Rev. Letters 21, 316 (1968).

[6]J. Barlow, E. Lillestol, L. Montanet, L. Tallone-Lombardi, C. D'Andlau, A. Astier, L. Dobrzynski, S. Wojcicki, A. M. Adamson, J. Duboc, F. James, M. Goldberg, R. A. Donald, R. James, J. E. Lys, and T. Nisar, Nuovo Cimento 50A, 701 (1967).

[7]W. Kienzle, B. C. Maglić, B. Levrat, F. Lefebvres, D. Freitag, and H. R. Blieden, Phys. Letters 19, 438 (1965). Also see the compilation by A. H. Rosenfeld et al., Rev. Mod Phys. 40, 77 (1968), and references therein.

[8]C. Defoix, J. Siand, P. Rivet, F. Shively, and B. Conforto, in the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (to be published).

[9]Among the accepted (MM) possibilities were Λ^0, Σ^0, $\Sigma^{\pm}$, and $\bar{K}N$ with or without neutral as well as charged pions.

[10]Such events comprised ~17% of the total sample and their inclusion or exclusion does not alter any conclusion contained in this Letter. They are excluded to make the sample as pure as possible.

[11]This observation is consistent with the peripheral argument that the t distribution should have the form $t/(t-m_k^2)^2$.

[12]We obtain this cross section in the following way. (a) We note that the forward regeneration ($K_2^0p \to K_1^0p$) amplitude $f_{21}(0)$ equals $\frac{1}{2}[f_+(0)-f_-(0)]$, where $f_+(0), f_-(0)$ are the forward elastic scattering amplitudes for $K^+n \to K^+n$ and $K^-n \to K^-n$. (b) We assume the $f(0)$'s to be imaginary [$\mathrm{Re}f(0) \ll \mathrm{Im}f(0)$] and take $\mathrm{Im}f_\pm(0) = (k/4\pi)\sigma_T^{\pm}$ (optical theorem). (c) We then write the differential cross section for regeneration in the forward direction, $d\sigma_{21}(0)/d\Omega = (k/8\pi)^2[\sigma_+ - \sigma_-]^2$ for given momentum (k) in the center-of-mass system. The σ_+ and σ_- cross sections are taken from the measured values of D. V. Bugg et al., Phys. Rev. 168, 1466 (1968). We obtain values of $d\sigma_{21}(0) = (0.2\ \mathrm{mb/sr})d\Omega$. This estimation is also in agreement with the experimental observation of $K_2^0p \to K_1^0p$ for K_2^0 momenta >2 GeV/c by A. Firestone et al., Phys. Rev. Letters 16, 556 (1966). They also find $f_{21}(0)$ to be substantially imaginary, in agreement with our assumption in (b) above. Experimentally, $d\Omega$ is taken to be 0.001 sr because our kinematics program would not accept any K_1^0 as being associated with the production vertex with a $d\theta > 0.02$ rad. Therefore, $\sigma_{21}(\sim 0) = \int_0^{0.001} (0.2\ \mathrm{mb/sr})d\Omega$. (d) If we assume that all the $K_1^0K_1^0$ events arise from φ events in which the K_2^0's regenerate K_1^0's in and about the forward direction of the K_2^0, we obtain a cross section of $K^-N \to \varphi$ + others to be $\gtrsim 100$ mb. We have considered the decay dependence of K_1^0 in flight and found its effects to be negligible.

[13]Such an occurrence would not, however, alter the establishment of the K_1K_1 enhancement since the quantum numbers of the $K_1^0K_1^0$ system are unique and independent of its production process.

[14]V. E. Barnes, P. J. Dornan, G. R. Kalbfleisch, G. London, R. Palmer, R. R. Rau, N. P. Samios, I. O. Skillicorn, M. Goldberg, K. Jaeger, C. Y. Chang, and J. Leitner, Phys. Rev. Letters 19, 964 (1967); R. Ammar, R. E. P. Davis, C. Hwang, W. Kropac, J. Mott, B. Werner, S. Dagan, M. Derrick, F. Schweingruber, and J. Simpson, Phys. Rev. Letters 19, 1071 (1967).

[15]The Breit-Wigner formula $m_0\Gamma_i(m)/[(m^2-m_0^2)^2 + m_0^2\Gamma_T^2(m)]$ for decay to channel i depends on the total width $\Gamma_T(m)$ in the denominator; $\Gamma_T(m) = \sum_i \Gamma_i(m)$, where the summation is over all channels. These partial widths Γ_i have a mass dependence of the form $\Gamma_i(m) = \Gamma_i(m_0)[q_i(m)/q_i(m_0)]^{2l+1}$, where $q_i(m)$ is the momentum of the decay products in the resonance c.m. frame for channel i. Consequently the exact form of the fit depends upon the branching fractions assumed. We have used the two extreme assumptions: (a) $\Gamma_T(m) \sim \Gamma_{K\bar{K}}(m)$ or (b) $\Gamma_T(m) \sim \Gamma_{\pi\pi}(m)$.

[16]Only an s-wave scattering length was used, since the most probably spin and parity of the state is $J^P = 0^+$. The next possible state, being 2^+, is not very likely.