rect in this region. Further work is in progress on this point.

We wish to acknowledge the important contributions of Professor R. G. Glasser, Mr. H. A. Rubin, and Professor B. Sechi-Zorn. In addition, we wish to acknowledge the valuable assistance of Mrs. Mary Resio, Mr. Richard Krider, and our student scanners.

---

*Work supported in part by the U. S. Atomic Energy Commission.

†Present address: Illinois Institute of Technology, Chicago, Illinois.

‡National Science Foundation Advanced Science Education Program Participant from Oberlin College, Oberlin, Ohio.

[1]T. H. Fields, G. B. Yodh, M. Derrick, and J. G. Fetkovitch, Phys. Rev. Letters 5, 69 (1960).

[2]J. H. Doede, R. H. Hildebrand, M. H. Israel, and M. Pyka, Phys. Rev. 129, 2808 (1963).

[3]E. Bierman, S. Taylor, E. L. Koller, P. Stamer, and T. Huetter, Phys. Letters 4, 351 (1963).

[4]R. Knop, R. A. Burnstein, and G. A. Snow, Phys. Rev. Letters 14, 767 (1965); M. Cresti, S. Limentani, A. Loria, L. Perruzzo, and R. Santangelo, Phys. Rev. Letters 14, 847 (1965).

[5]T. B. Day, J. Sucher, and G. A. Snow, Phys. Rev. Letters 3, 61 (1959).

[6]M. Leon and H. A. Bethe, Phys. Rev. 127, 636 (1962).

[7]P. Baillon, thesis, University of Paris, 1963 (unpublished).

[8]A description of the beam is given by B. Aubert, H. Courant, H. Filthuth, A. Segar, and W. Willis, in Proceedings of the International Conference on Instrumentation for High-Energy Physics at CERN, edited by F. M. Farley (North-Holland Publishing Company, Amsterdam, 1963).

[9]A. S. Wightman, Phys. Rev. 77, 521 (1950).

[10]T. B. Day, University of Maryland Technical Report No. 175, 1960 (unpublished).

[11]We use the value for the Σ^- lifetime of 1.615×10^{-10} sec, which is the weighted average of the value given in A. H. Rosenfeld et al., Rev. Mod. Phys. 36, 977 (1964); and C. Y. Chang, J. Steinberger, and T. H. Tan, Bull. Am. Phys. Soc. 9, 639 (1964).

[12]J. Marion and T. W. Bonner, Fast Neutron Physics (Interscience Publishers, Inc., New York, 1963), Pt. II, p. 2221, and references contained therein.

[13]This is the momentum of the neutron from a Σ^- decay at rest.

[14]For details of the hydrogen density measurement, see R. A. Burnstein, T. B. Day, B. Kehoe, B. Sechi-Zorn, and G. A. Snow, Phys. Rev. Letters 13, 66 (1964).

[15]B. d'Espagnat, Nuovo Cimento 20, 1217 (1961); R. Armenteros et al., in Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962, edited by J. Prentki (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 351; Phys. Letters 17, 344 (1965). C. Baltay et al., to be published.

OBSERVATION OF A PEAK IN $K^- + p \to \Lambda + \eta$ NEAR THRESHOLD*

D. Berley, P. L. Connolly,† E. L. Hart,‡ D. C. Rahm, D. L. Stonehill, B. Thevenet,§ W. J. Willis, and S. S. Yamamoto

Brookhaven National Laboratory, Upton, New York

(Received 8 September 1965)

We report here the results of measurements of the cross section for the reaction

$$K^- + p \to \Lambda + \eta \tag{1}$$

at a number of K^- momenta near the threshold. A sharp peak in the cross section is observed near the threshold. The excitation functions predicted by possible singularities in the reaction matrix are compared with the data.

The examples of Reaction (1) are found among events of the types

$$K^- + p \to \Lambda + \text{neutral missing mass}, \tag{2}$$

$$K^- + p \to \Lambda + \pi^+ + \pi^- + \pi^0. \tag{3}$$

The events were observed in approximately 150 000 pictures taken at the Brookhaven AGS with the 30-in. hydrogen bubble chamber exposed to a separated K^- beam at five momenta above the threshold for Reaction (1), which occurs at 724.5 MeV/c. The values of these momenta at the center of the bubble chamber were found to be 725, 741, 768, 802, and 820 MeV/c with a beam spread of ±0.7%. These momenta were measured by several methods, including values from $K^- \to \mu^- + \nu$ decays where the μ^- stops in the chamber and, particularly, the values of K^- momenta computed from the fitted momentum and angle of the Λ in the events interpreted as Reaction (1). (The mass of the η was taken to be 548.7 MeV/c^2.[1]) The measurements are in agreement, the latter being more accurate near threshold, where for a typical event the K^- momentum has an error of about 1 MeV/c.

The fraction of Reaction (2) which corresponds to η production is obtained by examining the mass distribution of the missing neutrals. The histogram of the square of the neutral missing mass is shown in Fig. 1 for two of the K^- incident momenta. The two sharp peaks in Fig. 1(a), from the run at 741 MeV/c, correspond to the π^0 and η masses. There is also a continuum arising from the apparent mass of the neutral system in the reactions

$$K^- + p \to \Sigma^0 + \pi^0, \tag{4}$$

$$K^- + p \to (\Lambda^0 \text{ or } \Sigma^0) + n\pi^0, \tag{5}$$

where n is 2 or 3. The continuum background in the region of the η peak is rather small.[2] Figure 1(b) shows the distribution from the run at a K^- momentum of 820 MeV/c, and the η peak has essentially disappeared. In Figs. 1(c) and 1(d) the $\pi^+\pi^-\pi^0$ mass distribution is shown for the same two K^- momenta. The η cross section is calculated as the sum of the decays into neutrals and the decays into $\pi^+\pi^-\pi^0$, with the latter increased by 22% to account for decays into $\pi^+\pi^-\gamma$.[1] The $\pi\pi\gamma$ decays can be kinematically separated from $\pi^+\pi^-\pi^0$ decays but are ambiguous with a similar number of events from $K^- + p \to \Sigma^0 + \pi^+ + \pi^-$, where the $\pi^+\pi^-$ and the γ from the decay of the Σ^0 happen to have a mass in the η region.

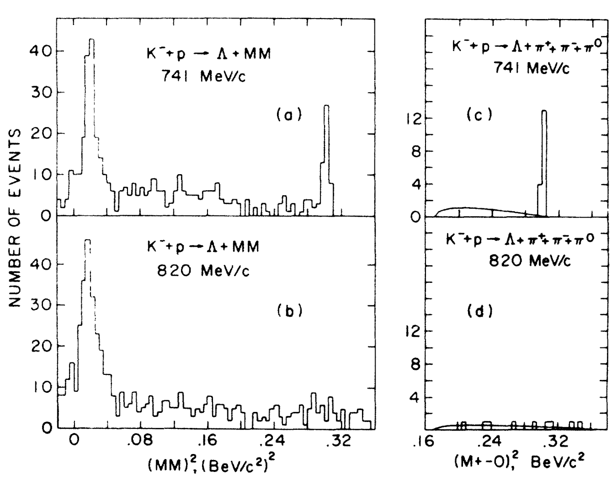

FIG. 1. (a) and (b) Distribution of the missing mass squared for zero-prong events associated with a kinematically fitted Λ [Reaction (2)], for K^- incident momenta of 741 and 820 MeV/c. (c) and (d) Distributions of the $\pi^+\pi^-\pi^0$ mass for events which give kinematic fits to Reaction (3), for the same two K^- momenta.

In order to study the increase of the η production just above threshold, the lowest momentum run was chosen such that, considering the energy loss of the K^- in the hydrogen, the threshold momentum is reached when the beam particle is near the center of the chamber. If the beam were truly monoenergetic, the threshold would correspond to a definite position in the chamber, but due to the spread in momentum, the point at which the threshold is reached is distributed over the central region of the chamber. Consequently, most of the $\Lambda\eta$ events occur in the upstream half of the chamber. Under these circumstances, the following method was used to evaluate the cross section.

The $\Lambda\eta$ events in the 725-MeV/c run were divided into three bins corresponding to the momenta 724.5-728.5, 728.5-732.5, and 732.5-736.5 MeV/c, using the K^- momentum determined from the production fitted to the η mass, as mentioned earlier. The path length for each momentum interval was determined by evaluating the integral

$$dL/dp = \int f(x,p)E(x)dx, \tag{6}$$

where x is the distance along the beam direction; $f(x,p)$ is the beam momentum distribution (assumed to be Gaussian in shape) with the central momentum as a function of x given by the range-momentum relation in hydrogen; and $E(x)$ is the relative probability of obtaining an event of this type at a given x, for a constant cross section.

The quantity $E(x)$ was measured from the distribution of $\Lambda + 2\pi$ events not involving η's, but with a similar Λ configuration, thereby including the effects of the decay and interaction of beam particles, as well as the scanning efficiency. The total path length, L, integrated over p, has been normalized to the value given by the number of τ decays observed.

The number of events in each of the momentum intervals is corrected for background by analyzing plots like Fig. 1, and is combined with the integrals of dL/dp over the corresponding momentum interval to give the value of the cross section for that interval. It may be noted that dL/dp has tails at high and low momenta given by the form of the beam momentum distribution. These are not well determined, since only the rms width of the beam distribution is measured well. However, the tails in dL/dp, and the corresponding events, are not used for evaluating the cross section. The momentum intervals used extend only about one-third further than the spread due to the energy loss in the hydrogen. For this reason, the cross sections are not very sensitive to the form of $f(x,p)$.

At the higher momenta, where the error on the K^- momentum is larger and the variation of the cross section less rapid, the subdivision of the individual runs is not carried as far. The run at 768 MeV/c has been divided into two regions, and the runs at 802 and 820 MeV/c have not been subdivided at all.

The resulting cross sections are plotted in Fig. 2(a) as a function of the momentum of the η in the $\Lambda\eta$ center-of-mass system. The c.m. system total energy is shown on a separate scale. The relation between the two scales is very nonlinear near threshold. The cross section exhibits a sharp peak just above threshold, with a maximum near 1 mb, to be compared with the $J=\frac{1}{2}$ unitarity limit of 3.6 mb, for a state with isospin equal to zero. It is very natural that in a two-body reaction the cross section should rise very sharply at threshold, and then perhaps fall slowly. The unusual aspect of the observed excitation function is the rapid decrease in the cross section.[3]

The angular distribution of the η's is given in Figs. 2(b) and 2(c), for two momentum intervals. The fact that these are consistent with isotropy suggests that the dominant angular-momentum states have $J=\frac{1}{2}$. Furthermore, the lack of a pronounced front-back asymmetry in the lower momentum interval, where $s_{1/2}$ would be favored over $p_{1/2}$ by the angular-momentum barrier, suggests that $s_{1/2}$ is the dominant state.

We have considered several possible interpretations for this peak: an effect arising from a large $s_{1/2}$ or $p_{1/2}$ scattering length, and an $s_{1/2}$ or $p_{1/2}$ resonance. In order to analyze the data in terms of a scattering length, we make use of the K-matrix analysis as developed by Dalitz.[4] This analysis, with zero effective range, has proved to be quantitatively successful[5] in the analysis of $K^- + p \to \Sigma + \pi$ reactions for c.m. system momenta up to at least 200 MeV/c, which is greater than the highest η momentum encountered in our experiment. The result for $s_{1/2}$ scattering length can be expressed as

$$\sigma_{\Lambda\eta} = \frac{2\pi}{k^2}\,\frac{r\,dq}{1+dq+(c^2+d^2)q^2},$$

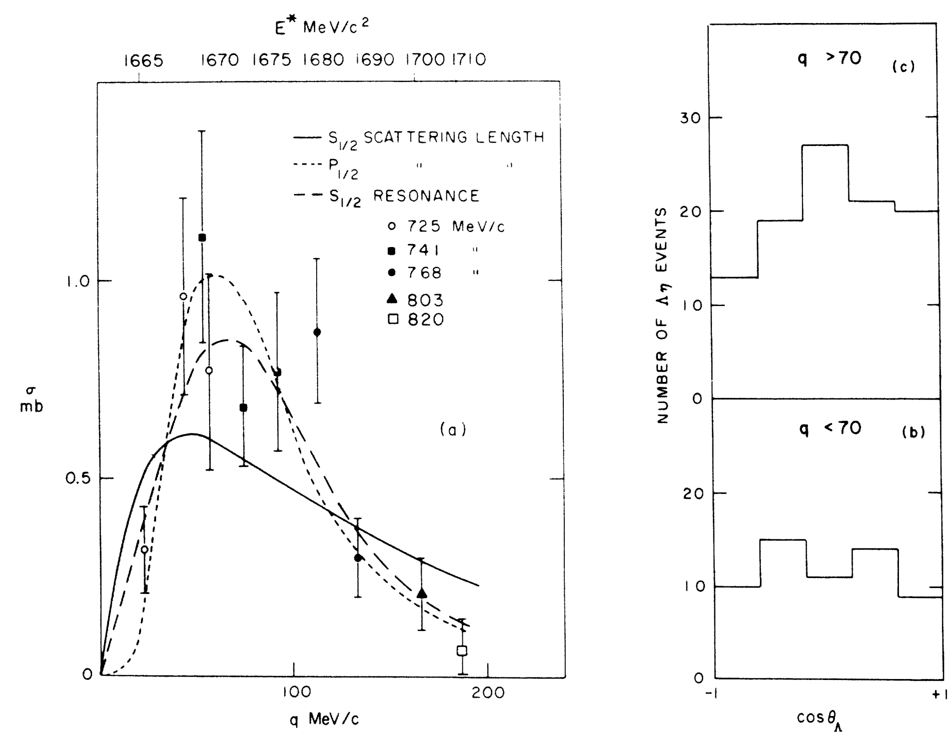

FIG. 2. (a) The cross section for $K^- + p \to \Lambda + \eta$, as a function of the center-of-mass momentum of the η. (b) The angular distribution of the $\Lambda\eta$ events, for η momenta below 70 MeV/c. (c) The angular distribution of the $\Lambda\eta$ events, for η momenta above 70 MeV/c.

where q = the η momentum, in units of (Fermi)$^{-1}$; $c+id$ = the $\Lambda\eta$ complex scattering length; r = a parameter which measures the coupling to channels other than K^-p, $0 \le r \le 1$; and k = momentum of the incoming K^-. The best fit to the $s_{1/2}$ scattering length, giving a χ^2 probability of 0.1%, is shown as a solid curve in Fig. 2. The fit is not very good primarily because it is difficult to reproduce the rapid fall of the cross section with the form of Eq. (2), which decreases no faster than q^{-1}. The value of the scattering length which gives the minimum χ^2 is $4+0.7i$ F, with $r=0.9$. Since the value of c is considerably larger than d, and larger than the expected range of nuclear forces, the possibility of a "virtual bound state"[6] exists if $c<0$. As Eq. (2) shows, measurements of $\sigma_{\Lambda\eta}$ cannot determine the sign of c. The bound state predicted for $c<0$ would be ~2 MeV below $\Lambda\eta$ threshold and would be very narrow, since, very crudely,[4,6] $\Gamma \sim (d/\mu_\eta c^3) = 2.3$ MeV, where μ_η is the reduced mass of the $\Lambda\eta$ system. An examination of the cross sections for $K^-+p \to \bar{K}^0+n$, $\Sigma^+ + \pi^-$, and $\Sigma^- + \pi^+$ in the 725-MeV/c run, with a momentum resolution four times larger than the predicted width, shows no evidence for such a peak. If c is positive, on the other hand, the only effects in other channels would be very small fluctuations due to the unitarity of the K matrix.

For a $p_{1/2}$ scattering length, the cross section is given by

$$\sigma_{\Lambda\eta} = \frac{2\pi}{k^2}\,\frac{rdq^3}{1+dq^3+(c^2+d^2)q^6}.$$

The dashed curve in Fig. 2 shows a fit with a χ^2 probability of 13%, which is better than for the $s_{1/2}$ scattering length. The best-fit scattering length is $(30.4+9.5i)$ (F)^3, with $r=0.3$. The large value of d overcomes the effect of the angular-momentum barrier to give a large cross section near threshold; the damping term in the denominator then causes a rapid decrease in the peak.

A Breit-Wigner resonance formula for an $s_{1/2}$ state gives a good fit to the data, as shown by the broken curve in Fig. 2. The $\Lambda\eta$ partial width, Γ_η, is proportional to q, and if Γ_η is assumed to be small compared to the total width Γ, so that Γ is approximately constant, the best fit has a χ^2 probability of 28%, with a resonance energy $E_0{}^* = 1666$ MeV/c^2, width $\Gamma = 22$ MeV/c^2, and partial-width product, evaluated at $E_0{}^*$, $(\Gamma_K\Gamma_\eta/\Gamma^2) = 0.039$. If, on the other hand, $\Gamma \sim \Gamma_\eta \propto q$, the resulting fit has a probability of 30%, with $E_0{}^* = 1675$ MeV/c^2, $\Gamma = 15$ MeV/c^2, $(\Gamma_K\Gamma_\eta/\Gamma^2) = 0.053$. Thus, the hypothesis of an $s_{1/2}$ resonance is in excellent agreement with the data.

A Breit-Wigner formula for a $p_{1/2}$ resonance gave rather poor fits to the data, at least with the total width assumed to be constant or varying as p^3, corresponding to the assumptions made in the $s_{1/2}$ case. A fit could be obtained by introducing further parameters to give a more complex momentum dependence to the widths.

The conclusions from the fits to these simple models is that the $T=0, s_{1/2}$ resonance provides the best fit to the data.[7] The $p_{1/2}$ scattering length also gives a reasonable fit, but the angular distributions, and the somewhat implausible value of the imaginary part of the scattering length, offer arguments against this hypothesis. The s-wave scattering-length hypothesis, which is perhaps a priori the most attractive model, does not give a good fit; however, it may be that the zero-range theory is inadequate in the present case.[8]

This question could be resolved if effects of the resonance could be found in other channels, far removed from threshold, such as $K^-+p \to \Sigma^\pm + \pi^+$. However, this is complicated by the small size of the effects allowed by the $s_{1/2}$ unitarity limit,[9] and by the fact that the $Y_1{}^*(1660)$ occurs at about the same mass in these channels. The reaction $K^-+p \to \Sigma^0+\pi^0$ would be ideal, since it is a pure $T=0$ state, but it is not easily accessible experimentally.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

†Presently at CERN, Geneva, Switzerland.

‡Presently at Istituto di Fisica, Università di Pisa, Pisa, Italy.

§Presently at Laboratoire de Physique Corpusculaire et Haute Energie, Centre d'Etudes Nucleaires, Saclay, Gif-sur-Yvette, Seine-et-Oise, France.

[1]A. H. Rosenfeld, A. Barbaro-Galtieri, W. H. Barkas, P. L. Bastien, J. Kirz, and M. Roos, Rev. Mod. Phys. 36, 977 (1964).

[2]The continuum arising from Reaction (4) has an upper limit at 0.2 (BeV/c^2)^2.

[3]P. L. Bastien, J. P. Berge, O. I. Dahl, M. Ferro-Luzzi, D. H. Miller, J. J. Murray, A. H. Rosenfeld, and B. Watson, Phys. Rev. Letters 8, 114 (1962). In one of the early observations of the η, these authors were, as they said, disconcerted by the very small cross section for Reaction (1) for K^- of 850 MeV/c, compared to the large value at 760 MeV/c.

[4]R. Dalitz and S. F. Tuan, Ann. Phys. (N.Y.) 10, 307 (1960).

[5]J. K. Kim, Phys. Rev. Letters 14, 29 (1965).

[6]R. Dalitz, Rev. Mod. Phys. 33, 471 (1961).

[7]W. Y. Chan, K. H. Ju, E. N. Kladnitskaya, G. I. Kopylov, A. A. Kuznetsov, N. M. Melinkova, N. Dinh-Tu, and E. S. Sokolova, Proceedings of the International Conference on High-Energy Physics, Dubna, 1964 (to be published). These authors observe a possible enhancement in the $\Lambda+\gamma$ effective-mass distribution from events produced by high-energy pions in a propane bubble chamber. They identify this enhancement with the formation of a $\Lambda\eta$ state with small Q value, where the η decays to two γ rays, one of which is observed. Their observation may perhaps be connected with the effect reported here.

[8]The use of a full matrix of effective ranges in each channel introduces many more parameters. If a real effective range of 1 F in the $\Lambda\eta$ channel is assumed, the effect on $\sigma_{\Lambda\eta}$ at $q=190$ MeV/c is to reduce the cross section by only 40%, if $c<0$. For $c<0$, or for smaller q, the effect is less.

[9]For example, the maximum possible size of the resonant peak in $K^-+p\rightarrow\Sigma^0+\pi^0$ is 0.8 mb.

ERRATUM

CP-NONCONSERVING DECAY $K_1{}^0\rightarrow\pi^++\pi^-+\pi^0$. Jared A. Anderson, Frank S. Crawford, Jr., Robert L. Golden, Donald Stern, Thomas O. Binford, and V. Gordon Lind [Phys. Rev. Letters 14, 475 (1965)].

Our paper contains an internal inconsistency in sign convention. Our corrected results for $y=[(m_2-m_1)/|m_2-m_1|]\mathrm{Im}(a_1/a_2)$ in Eqs. (2) and (3) are $y=-1.00\pm0.65$ and -0.80 ± 0.55, respectively. The sign of y should also be reversed in references 7 and 10, and in the labeling of Figs. 1 and 2. We are indebted to Y. Tomozawa for his observation.