etc.

[7]See for example, C. Schmid, Phys. Rev. Letters 20, 689 (1968); G. Höhler, J. Baacke, and G. Eisenbeiss, Phys. Letters 22, 203 (1966).

[8]G. Höhler, J. Baacke, H. Schlaile, and P. Sonderegger, Phys. Letters 20, 79 (1966).

[9]Although beyond $-t \approx 1.0$ (GeV/c)^2, only solution (b) of Ref. 3 disagrees strongly with our polarization data, only the fit of Ref. 4 is also consistent with the differential cross-section data at large $-t$.

[10]N. E. Booth, Phys. Rev. Letters 21, 465 (1968).

[11]A double sign change may also be possible. See F. J. Gilman, H. Harari, and Y. Zarmi, Phys. Rev. Letters 21, 323 (1968).

[12]In Ref. 4 the P and P' flip amplitudes were neglected so $A_0'B_0{}^*$ is necessarily zero.

[13]Since complete elastic cross-section data are not yet available at this momentum we have used values of $(d\sigma/dt)_\pm$ and $(d\sigma/dt)_0$ calculated from the Regge-pole model of Ref. 4. This model fits cross-section data between 3 and 10 GeV/c fairly well, at least out to $-t = 1.5$.

[14]D. Drobnis et al., Phys. Rev. Letters 20, 274 (1968); P. Bonamy et al., Phys. Letters 23, 501 (1966).

[15]See for example, C. C. Ting, L. W. Jones, and M. L. Perl, Phys. Rev. Letters 9, 468 (1962).

PARTIAL-WAVE ANALYSIS OF THE SEQUENTIAL REACTION $K^-N \to Y_1^*(1385)\pi \to \Lambda\pi\pi$ IN THE CENTER-OF-MASS ENERGY RANGE 1600-1740 MeV*

W. H. Sims, J. R. Albright, E. B. Brucker, J. T. Dockery,† J. E. Lannutti, J. S. O'Neall,‡ and B. G. Reynolds
The Florida State University, Tallahassee, Florida

and

J. H. Bartley, R. M. Dowd, A. F. Greene,§ and J. Schneps
Tufts University, Medford, Massachusetts

and

M. Meer,‖ J. Mueller, M. Schneeberger, and S. Wolf
Brandeis University, Waltham, Massachusetts
(Received 3 September 1968)

The reaction $K^-n \to \Lambda\pi^-\pi^0$ for c.m. energies from 1600 to 1740 MeV is found to proceed entirely through the two-body $Y_1^*(1385)\pi$ state. A partial-wave analysis of the $Y_1^*(1385)\pi$ state implies s-channel production of $Y_1^*(1660)$, $Y_1^*(1765)$, and a $Y_1^*(1700)$ with the subsequent decay of each into $Y_1^*(1385)\pi$. A determination of the mass, width, elasticity parameter, spin, and parity of each of these s-channel resonant states has been made.

The analysis discussed in this Letter considers, in a formation experiment, the pure $I=1$ $\Lambda\pi\pi$ final state and the sequential decay $Y^* \to \Sigma(1385)\pi \to \Lambda\pi\pi$. This assumed sequential decay offers certain advantages for analysis since if a resonant state decays through the $\Sigma(1385)$ which has spin $\frac{3}{2}$, and a π which has spin 0, then the production angular distribution of the $\Sigma(1385)$ will be free of the Minami ambiguity and will, in principle, uniquely determine the spin and parity J^P of the parent resonant state.[1] However, in this energy region, interference effects and overlapping $\Sigma(1385)$ bands are expected to distort this and other distributions[2] as either pion may form a $\Sigma(1385)$ with the lambda and Bose statistics are required for the final-state pions. Since direct s-channel production is believed to dominate the $\Sigma(1385)\pi$ state at this energy,[3] a partial-wave analysis is feasible provided the distorting effects mentioned above are taken into account. The isobar-model formulation of Deler and Valladas,[4] hereinafter referred to as DV, accounts for these effects and is used in the following partial-wave analysis.

The experimental data for this analysis were obtained from an exposure of the Brookhaven National Laboratory 30-in. deuterium-filled bubble chamber to K^- beams of momenta 670, 720, 770, 810, 850, and 910 MeV/c. The reaction analyzed was $K^-n(p) \to \Lambda\pi^-\pi^0(p)$, where (p) indicates the spectator proton. Fits were accepted only for those events having a measurable spectator proton, and a χ^2 probability $\geq 5\%$. Events accepted in this analysis also were required to have a spectator momentum less than 280 MeV/c. The spectator-momentum distribution of these selected events is well described by the Fourier-transformed Hulthén wave function. A total of 555 events was selected for the partial wave analysis and divided into six c.m. energy intervals from 1600 to 1740 MeV. Corrections based on the lambda lifetime were applied to the sample for events missed due to lambdas which decayed either close to the production vertex or outside the fiducial volume. The absolute cross sections[5] were obtained using a normalization factor deduced by equating our cross section for the companion reaction $K^-p \to \Lambda\pi^-\pi^+$ measured in deuterium[6] to that measured in hydrogen by Bastien and Berge.[7]

Since the DV formulation is well described in Ref. 4, only its application will be discussed here. For each partial wave this formulation predicts the Dalitz-plot density distribution for three-body final-state production via an intermediate two-body state. In this experiment the intermediate state is $\Sigma(1385)\pi$. Instead of fitting the Dalitz plot directly, we chose to work with three conventional projected distributions: (a) the square of the effective mass of the $\Lambda\pi^{-,0}$ system, (b) the $\Sigma(1385)$ decay angular distribution [the cosine of the angle between the lambda direction in the $\Sigma(1385)$ rest frame and the direction of the $\Sigma(1385)$ in the overall c.m. system] for those events having $1366 \leq M_{\Lambda\pi} \leq 1404$ MeV, and (c) the kinetic energy of the lambda in the overall c.m. system for those events with $|T_{\pi^-} - T_{\pi^0}| \leq 19.6$ MeV (i.e., a band along the T_Λ axis of the Dalitz plot).[8]

The percent contribution of each partial wave ($SD1$, $PP1$, $PP3$, $DS3$, $DD5$, and $FP5$) and a three-body phase space was determined by the χ^2 minimization technique.[9] Here, it must be noted that the three experimental histograms for each energy interval were fitted simultaneously. The calculated distributions (a), (b), and (c) were normalized to the total number of events on the Dalitz plot in each energy interval.

The nomenclature $SD1$, etc., is of the form $LL'2J$ and denotes an L wave between the incident beam and target, an L' wave between the $\Sigma(1385)$ and the odd pion, and total spin J. In order to decrease the number of unknown parame-

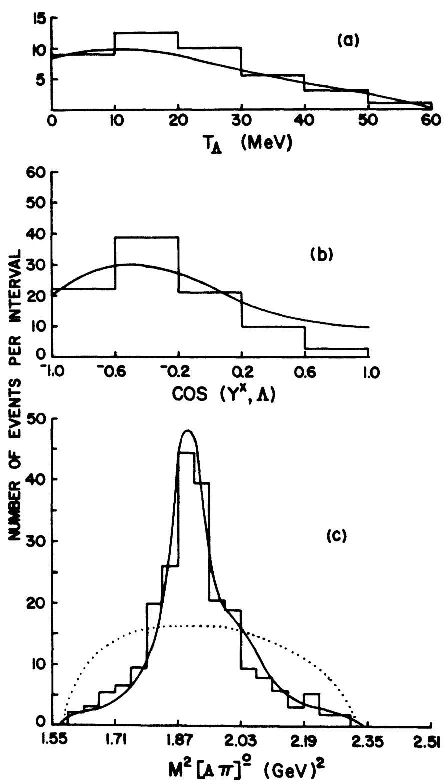

FIG. 1. For the center-of-mass interval 1650-1670 MeV, (a) the center-of-mass kinetic energy of the lambda for events with $|T_{\pi_0} - T_{\pi^-}| \leq 19.6$ MeV, (b) the $\Sigma(1385)$ decay angular distribution for events in the $\Sigma^{0,-}(1385)$ bands, and (c) the square of the effective mass of the $\Lambda\pi^{-,0}$ system. The solid curve is the best-fit solution; the dotted curve in (c) is three-body phase space. The ordinates represent real numbers of events with a lambda lifetime weight of ~10%. In (c) each event is plotted twice.

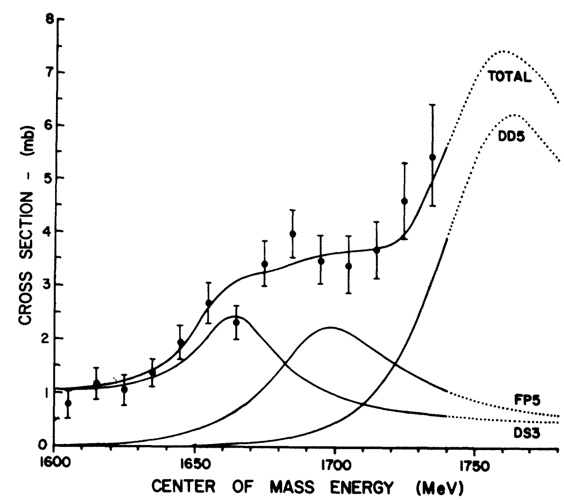

FIG. 2. Breit-Wigner plus background fits to the partial waves $DS3$, $DD5$, and $FP5$. Their sum may be compared with the indicated experimental cross section points. The dotted lines are extensions of the fits outside of the energy region of this experiment. To obtain the smooth curves the Dalitz-plot projections were fitted to determine the amount of each partial wave present, then this amount was expressed in terms of cross section and fitted to Breit-Wigners as indicated in the text.

Table I. Resonance parameters.

Partial Wave	J^P	E_0 (MeV)	Γ_0 (MeV)	$X_{\bar{K}N}X_{Y\pi}$ [a]	$\sigma_{Y\pi}$ at $E=E_0$ (mb)	Percent χ^2 probability	Percent background[b] at $E=E_0$
$DS3$	$\frac{3}{2}^-$	1665 ± 6	37 ± 10	0.031 ± 0.006	1.8 ± 0.4	85	27 ± 8
$FP5$	$\frac{5}{2}^+$	1700 ± 6	62 ± 14	0.030 ± 0.005	2.2 ± 0.4	10	0 ± 5
$DD5$	$\frac{5}{2}^-$	1765 ± 10	86 ± 23	0.105 ± 0.040	6.2 ± 2.5	80	0 ± 5

[a] $X_{Y\pi}$ here is the elasticity parameter for decay into $\Lambda\pi\pi$ via the $\Sigma(1385)\pi$ mode.
[b] The background is taken to be nonresonant $\Sigma(1385)\pi$.

ters, contributions from the partial waves $PF3$, $DD3$, $DG5$, and $FF5$ are ignored since it was expected that they would be suppressed on decay relative to $PP3$, $DS3$, $DD5$, and $FP5$, respectively, by a centrifugal barrier factor.

The best fit solution was found to contain significant amounts of only the $DS3$, $DD5$, and $FP5$ waves, and had an overall χ^2 probability of 90%. Alternative solutions were rejected as having improbable confidence levels ($\lesssim 1\%$) and/or severe energy discontinuities. The fit of the preferred solution to the experimental histograms in the 1660-MeV interval is shown in Fig. 1. The data are well described by the intermediate $\Sigma(1385)\pi$ state and do not require any three-body phase space as is illustrated in Fig. 1(c). The cross sections attributed to each partial wave by the best-fit solution were fitted by a general Breit-Wigner plus nonresonant background in that partial wave. The fitted curves are displayed in Fig. 2 and the resonance parameters are given in Table I. Our experiment does not cover a large enough energy region to indicate with certainty that the $FP5$ and $DD5$ waves are indeed resonant; nonetheless, the rather good agreement of their fitted resonance parameters with current values suggests that such an interpretation may be valid. We therefore conclude that our data support the existance of three resonant states—$\Sigma(1660)$, $\Sigma(1700)$,[10] and $\Sigma(1765)$ with $J^P = \frac{3}{2}^-$, $\frac{5}{2}^+$, and $\frac{5}{2}^-$, respectively, which decay via $\Sigma(1385)\pi$.

We wish to express our appreciation to G. Valladas for helpful communications and to R. F. Peierls for suggesting this analysis. We are grateful to R. H. Bradley for the use of his minimization routine. We also wish to thank the particle physics staff and computing center personnel at our respective universities for their help in data acquisition and reduction.

---

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

†Present address: Office of the Chief of Staff, U. S. Army, Washington, D. C.

‡Present address: Brookhaven National Laboratory, Upton, New York.

§Present address: U. S. Atomic Energy Commission, Washington, D. C.

‖Present address: General Electric Cambridge Information Systems, Cambridge, Massachusetts.

[1] See, for example, R. D. Tripp, in Strong Interactions, Proceedings of the International School of Physics "Enrico Fermi," Course XXXIII (Academic Press, Inc., New York, 1966), p. 70.

[2] R. H. Dalitz and D. H. Miller, Phys. Rev. Letters 6, 562 (1961).

[3] The $\Sigma(1385)$ production angular distributions observed in this experiment favor s-channel production, although precise interpretation is difficult due to interference effects and overlapping resonant bands. D. O. Huwe [University of California Radiation Laboratory Report No. UCRL 11291 (unpublished)] indicates that peripheral production of $\Lambda\pi\pi$ or $\Sigma(1385)\pi$ becomes important at ~2 GeV—far above the energy of this experiment.

[4] B. Deler and G. Valladas, Nuovo Cimento 45A, 559 (1966). A similar formulation has been developed by M. Olsson and G. B. Yodh, Phys. Rev. Letters 10, 353 (1963), and Phys. Rev. 145, 1309, 1327 (1966). For a somewhat different approach see J. M. Namysowski, M. S. K. Razmi, and R. G. Roberts, Phys. Rev. 157, 1328 (1967).

[5] A more detailed discussion of the cross section determination is given by J. H. Bartley, et al. (to be published).

[6] The Fermi motion of the neutron target was unfolded using a technique similar to that discussed by R. Kraemer et al., Phys. Rev. 136, B496 (1964).

[7] P. L. Bastien and J. P. Berge, Phys. Rev. Letters 10, 188 (1963). In order to set the scale of the cross sections while maintaining the shape we have used a single normalization factor over the entire energy range of this experiment. The cross sections in Ref. 5, as derived in this manner, agree within errors with the compilation of J. Porte as discussed by T. Meyer, in the Proceedings of the Heidelberg International Conference on Elementary Particles, Heidelberg, Germany, 1967, edited by H. Filthuth (North-Holland Publishing Company, Amsterdam, The Netherlands, 1968), and

with the more recent work of the Pisa-Brookhaven-Yale Collaboration: L. Bertanza, et al., Phys. Rev. (to be published).

[8]Normalized Dalitz coordinates are used throughout this analysis in order to minimize effects due to dividing data into center-of-mass intervals of nonzero width. For a similar application of the restrictions on T_Λ, see D. Berley et al., in the Proceedings of the Twelfth International Conference on High Energy Physics, Dubna, U.S.S.R., 1964 (Atomizdat., Moscow, U.S.S.R., 1966), Vol. I, p. 565.

[9]The partial waves considered in this analysis add incoherently. Since the direct three-body reaction was seen to be small we ignored the possible interference effects between this process and the partial waves with the same J^P in order to reduce the numbers of parameters to be fitted.

[10]The $\frac{5}{2}^+$ effect with a central energy of 1700 MeV and width of 62 MeV does not agree closely with the 1680- and 120-MeV values reported in a production experiment by M. Derrick, T. Fields, J. Loken, R. Ammar, R. E. P. Davis, W. Kropac, J. Mott, and F. Schweingruber, Phys. Rev. Letters 18, 266 (1967). It is possible that the large width and shift in position seen by these authors is due in part to a superposition of $\Sigma(1660)$ and $\Sigma(1700)$, both of which seem to have a $\Sigma(1385)\pi$ decay mode.

SMALL-ANGLE pd SCATTERING IN THE MOMENTUM RANGE 1.3 TO 1.5 GeV/c

L. M. C. Dutton* and H. B. van der Raay
Department of Physics, University of Birmingham, Birmingham, England
(Received 26 July 1968)

The elastic and quasielastic scattering of incident protons by a deuterium target, over the angular range 20-70 mrad in the laboratory system, has been determined using a sonic spark-chamber system. Data were obtained at incident momenta of 1.29, 1.39, and 1.54 GeV/c and analyzed to determine the ratio of the real to imaginary parts of the pn forward scattering amplitude. Satisfactory agreement with the predictions of dispersion-relation calculations was obtained.

In a previous paper,[1] the results of the pd small-angle scattering experiment performed at an incident momentum of 1.69 GeV/c were analyzed to yield α_n, the ratio of the real to imaginary parts of the spin-independent forward scattering amplitude, which was shown to be in good agreement with the dispersion-relation calculations of Carter and Bugg.[2] In the present experiment further data were obtained at incident momenta of 1.29, 1.39, and 1.54 GeV/c, over the angular region 20-70 mrad in the laboratory system. In order to determine α_n from these data, the differential cross section was written in terms of the pp and pn scattering amplitudes taking into account Coulomb interference, nuclear interference, and double-scattering terms, according to the formalism of Harrington.[3] The appropriate parameters for the pp scattering amplitude must be known before the pn parameters can be extracted from data on pd scattering; these parameters have already been determined[4] at the incident momenta of the present experiment.

The experimental arrangement used was identical with that described in Ref. 4, except that in the present case, high-purity deuterium was liquified into the target appendix. The magnetic spectrometer, which consisted of a series of sonic spark chambers and a nuclear-resonance-stabilized magnet, has a momentum resolution of 0.5%, so that, whereas events involving the production of one or more pions could be easily resolved, those protons resulting from elastic pd scattering could not be resolved from the "quasielastic" scatters in which the deuteron was unbound in the final state. An expression for the sum of these two processes has been derived by Harrington[3] and was used in the analysis of the present data.

The differential cross section for pd scattering was written as

$$d\sigma/d\Omega=[|f_C|^2+(\mathrm{Re}f_p)^2+(1+\beta_p^2)(\mathrm{Im}f_p)^2+2(\mathrm{Re}f_p\mathrm{Re}f_C+\mathrm{Im}f_p\mathrm{Im}f_C)]+[(\mathrm{Re}f_n)^2+(1+\beta_n^2)(\mathrm{Im}f_n)^2]$$
$$+2[\mathrm{Re}f_n(\mathrm{Re}f_p+\mathrm{Re}f_C)+\mathrm{Im}f_n(\mathrm{Im}f_p+\mathrm{Im}f_C)+\beta_p\beta_n\,\mathrm{Im}f_p\,\mathrm{Im}f_n]S(q)+(2/k)[M(\mathrm{Im}f_p+\mathrm{Im}f_n)$$
$$-N(\mathrm{Re}f_p+\mathrm{Re}f_n-|f_C|)]+(1/k)[M^2+N^2]. \quad (1)$$