Study of $\Sigma(1385)\pi$ Production near the $\Lambda(1520)$ Resonance*

Shu-bon Chan, Janice Button-Shafer, Stanley S. Hertzbach, and Richard R. Kofler
University of Massachusetts, Amherst, Massachusetts 01002

and

Michel Schiff†
Yale University, New Haven, Connecticut 06520
(Received 13 November 1970)

We have studied the production mechanism of the reaction $K^-p \to \Sigma(1385)\pi$ with the total energy in the vicinity of the $\Lambda(1520)$ resonance. Two different analysis techniques were used: partial waves and moments. The results establish the decay mode $\Lambda(1520) \to \Sigma(1385)\pi$. Conclusions on $\frac{3}{2}^-$ octet-singlet mixing are presented.

Early in 1963 the authors of the well-known analysis of the $\Lambda(1520)$ stated that their $\Lambda\pi^+\pi^-$ data neither prohibited nor demanded $\Sigma(1385)$ production.[1] Reports of $\Lambda(1520) \to \Sigma(1385)\pi$ have been made by Cline, Laumann, and Mapp[2] and Burkhardt *et al.*[3] This experiment represents 13 times more data than Ref. 3.

It has been suggested that the observed $\frac{3}{2}^-$ physical states $\Lambda(1520)$ and $\Lambda(1690)$ are mixed states of the SU(3) singlet state $|\Lambda^1\rangle$ and the $I=0$ octet member $|\Lambda^8\rangle$, according to the following equations[4-6,3]:

$$|\Lambda(1520)\rangle = \sin\theta|\Lambda^8\rangle + \cos\theta|\Lambda^1\rangle,$$
$$|\Lambda(1690)\rangle = \cos\theta|\Lambda^8\rangle - \sin\theta|\Lambda^1\rangle, \tag{1}$$

where θ is the mixing angle. A sensitive way to study this mixing phenomenon is to consider the decay mode $\Lambda(1520) \to \Sigma(1385)\pi$, since only the $|\Lambda^8\rangle$ of Eq. (1) contributes to this decay.

Exposures were taken with the Brookhaven National Laboratory (BNL) 30-in. hydrogen bubble chamber. The momentum settings of the incident K beam were 375 and 415 MeV/c, with a spread of about 40 MeV/c in the chamber. In 180 000 pictures approximately 7000 vee (two-prong) events were double-scanned and measured. After applying selection criteria and cutoffs, we obtained 2590 good $\Lambda\pi^+\pi^-$ events.

We calculated the cross section versus incident momentum for $K^-p \to \Lambda\pi^+\pi^-$ with τ normalization.[7] At $E_{\mathrm{c.m.}} \approx 1520$ MeV, the cross section reaches a peak of 3.2 mb with background of 1.0–1.3 mb. Figure 1(a) presents the $\Lambda\pi^+$ mass-squared spectrum; and Figure 1(b) shows the $\Lambda\pi^+\pi^-$ cross section as a function of incident momentum.

Our first analysis was very similar to techniques developed by several authors.[8-10] The material which follows was drawn from Peierls[11] and Olsson and Yodh.[9]

We assume that the interaction went partially through the quasi-two-body state $\Sigma(1385)\pi_2$, with $\Sigma(1385)$ decaying subsequently into $\Lambda\pi_1$. Then

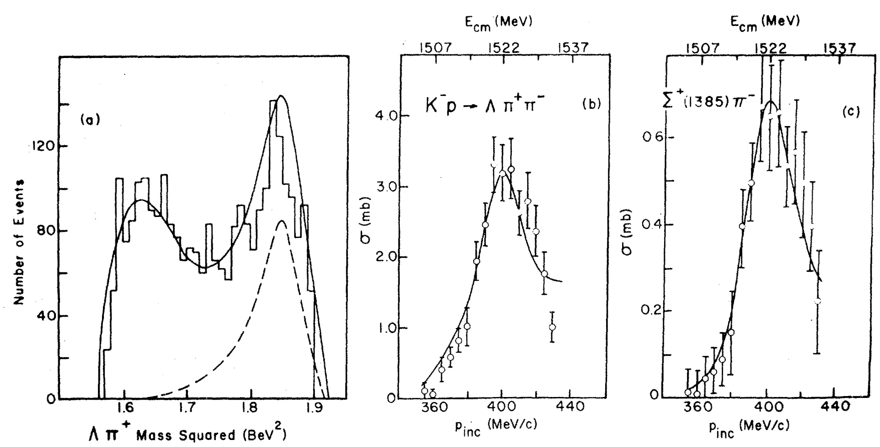

FIG. 1. (a) $M_{\Lambda\pi^+}{}^2$ from data of all energies, with average fit. The dashed curve is calculated $\Sigma^+(1385)$ production. (b) $K^-p \to \Lambda\pi^+\pi^-$ cross section (with a crude curve). (c) Weighted $\Lambda\pi^+\pi^-$ data representing pure $\Sigma^+(1385)\pi^-$. The curve is a best fit with the use of Eq. (5).

the matrix element is

$$\langle\pi_2(\pi_1\Lambda)|T|K^-p\rangle \propto A^{JL_iL_f}\sum_{\nu_3\mu_I} d_{\nu_3\mu_3}{}^{1/2}(\omega_3)C(1,\tfrac{1}{2},\tfrac{3}{2};0,\nu_3)C(L_f,\tfrac{3}{2},J;0,\mu_I)d_{\mu_I\nu_3}{}^{3/2}(\Psi_3)\exp(i\mu_I\varphi)$$
$$\times C(L_i,\tfrac{1}{2},J;0,-\lambda_p)d_{-\lambda_p\mu_I}{}^{J}(\theta_I)[1+i(M_{31}-M_I)/\Gamma_I]^{-1}, \qquad (2)$$

where μ_3, λ_p, μ_I are helicities of Λ, p, and $\Sigma(1385)$ in the c.m. frame; the last factor is the Breit-Wigner amplitude for the $\Sigma(1385)$; L_i and L_f are the orbital angular momenta for the K^-p and $\Sigma(1385)\pi$ systems, respectively; Ψ_3 gives the Λ direction in the Σ rest frame; φ gives the helicity azimuth of the Σ decay; θ_I is the production angle of the Σ; and the factor $d^{1/2}(\omega_3)$ relates Λ rest frames reached from the c.m. and the Σ rest frame. The reaction amplitude is $A^{JL_iL_f}$. We write Eq. (2) for each resonance case as

$$\langle\pi_m(\pi_n\Lambda)|T|K^-p\rangle \propto A^{JL_iL_f}f_{n3}. \qquad (3)$$

With total isospin designated, and $\pi_1\equiv\pi^-$, $\pi_2\equiv\pi^+$, we have

$$\langle\pi^-\pi^+\Lambda|T|K^-p\rangle \propto 2^{-1/2}A_1{}^{JL_iL_f}(-f_{13}+f_{23})+3^{-1/2}A_0{}^{JL_iL_f}(f_{13}+f_{23}). \qquad (4)$$

Background amplitudes $B_I{}^{JL_iL_f}$ (nonresonant $\Lambda\pi$ systems) are included by adding terms similar to those of Eq. (4), but lacking the $\Lambda\pi$ Breit-Wigner amplitude in f_{n3}.

The program ISOBAR[9] calculated $M_{\Lambda\pi^\pm}{}^2$ spectra and distributions in $\hat{K}\cdot\hat{\Lambda}$, $\hat{K}\cdot\hat{\pi}^+$, and $\hat{K}\cdot\hat{\pi}^-$ for given input values of $A_I{}^{JL_iL_f}$ and $B_I{}^{JL_iL_f}$. The values of the input amplitudes were optimized through a minimum-χ^2 search carried out with Humphrey's program MINFUN.[12] Events were divided into three bins centered at $E_{\text{c.m.}}=1515$, 1523, and 1531 MeV. With the number of degrees of freedom equal to 84 in each case, the χ^2 values were 81, 132, and 167 for low, middle, and high energies, respectively.

Figure 2 is a plot of the relative amplitudes obtained in fitting the data of the central energy bin. [The solid and dotted lines are resonant $\Sigma(1385)\pi$ amplitudes, while the dashed lines are background $\Lambda\pi\pi$ amplitudes.] The notation used

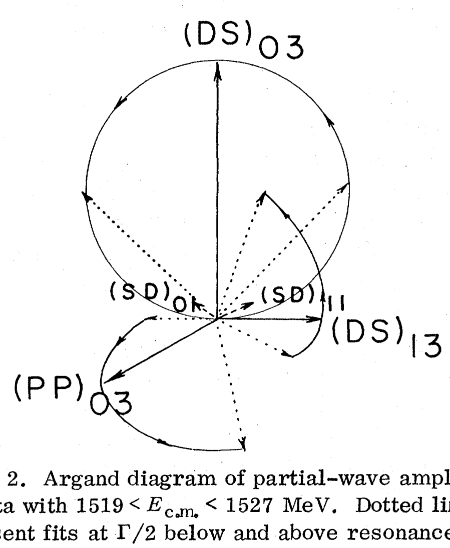

FIG. 2. Argand diagram of partial-wave amplitudes for data with $1519 < E_{\text{c.m.}} < 1527$ MeV. Dotted lines represent fits at $\Gamma/2$ below and above resonance.

is $(L_iL_f)_{I,2J}$. We see that the $(DS)_{0,3}$ wave is the predominant wave and also that its variation with energy is consistent with its being 100% resonant.

Another investigation to see whether the $\Sigma(1385)\pi$ events came from the decay of $\Lambda(1520)$ was made by using the "moment method," introduced by Byers and Fenster for $F_J\to F_{1/2}+B_0$.[13,14] Here we treat $F_J\to F_{3/2}B_0$, namely, $F_J\to\Sigma(1385)\pi$.[15] To calculate moments, we combine the events with $M(\Lambda\pi^\pm)$ under the $\Sigma^+(1385)$ or $\Sigma^-(1385)$ peak, since the interference effect between $\Sigma^+(1385)$ and $\Sigma^-(1385)$ was thereby canceled.[16]

The experimental values of the odd-l $I\langle T_{lm}\rangle$, obtained from either the longitudinal or transverse component of the Λ polarization, are all consistent with zero. We conclude that the intermediate state is nearly pure in spin and parity, and that its decay proceeds through only the lower-l wave.

The I, $I\langle T_{20}\rangle$, $I\langle T_{21}\rangle$, and $I\langle T_{22}\rangle$ are obtained from moments in the $\Sigma(1385)$ decay distribution. Their predicted values depend upon the spin and parity of the parent as well as the $\Sigma(1385)$ production angle θ.[15,17] The fit with the best hypothesis $F_{3/2^-}\to F_{3/2^+}B_{0^-}$ improved markedly as mass restrictions were tightened for either the $\Lambda(1520)$ or the $\Sigma(1385)$; the χ^2 was 57.6, 26.5, and 14.5 (with ten degrees of freedom) for parent-daughter mass selections which were wide-wide, narrow-wide, and narrow-narrow, respectively. ("Wide" means 1507–1537 or 1350–1420 MeV; "narrow" means 1512–1528 or 1362–1402 MeV.)

The χ^2 for parent $J^P=\frac{3}{2}^-$ was far lower than for other J^P hypotheses for all mass selections; for the "narrow-narrow" choice, the χ^2 values were 133, 14.5, 146, 222, and 121 for $J^P=\frac{1}{2}^\pm$, $\frac{3}{2}^-$, $\frac{3}{2}^+$, $\frac{5}{2}^-$, and $\frac{5}{2}^+$. This is consistent with the known

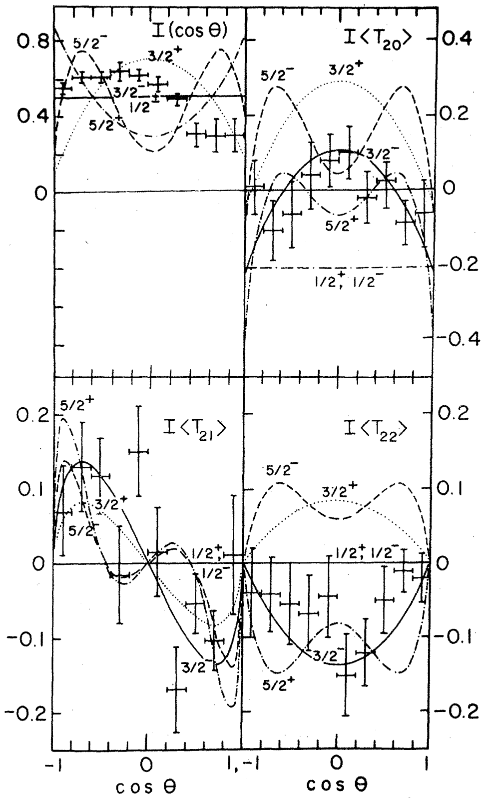

FIG. 3. Intensity I and $I\langle T_{lm}\rangle$ for $\Sigma^+(1385)$ and $\Sigma^-(1385)$ data combined versus production cosine. Curves represent predictions for various J^P intermediate states (Refs. 15 and 17). Solid curves represent the preferred hypothesis $J^P=\frac{3}{2}^-$.

spin and parity of the $\Lambda(1520)$ and the spin and parity of the dominant $I=1$ background amplitude

The experimental evaluations of $I\langle T_{lm}\rangle(\theta)$ for the "narrow-narrow" mass cuts are compared with theory in Fig. 3.

To the authors' knowledge, this is the first complete moment analysis for the case of $F_J \rightarrow F_{3/2}B_0$, $F_{3/2}\rightarrow F_{1/2}B_0$, $F_{1/2}\rightarrow F_{1/2}'B_0$.

To isolate $\Sigma^+(1385)$ production, we used only the amplitudes $A_I^{JL_iL_f f_{23}}$ [Eq. (4)] from our partial-wave analysis and generated the $M_{\Lambda\pi^+}{}^2$ spectrum without using $\Sigma^-(1385)$ or nonresonant $\Lambda\pi$ amplitudes. Curves like those of Fig. 1(a) were generated for the data at 1515, 1523, and 1531 MeV. A ratio for production of $\Sigma^+(1385)\pi^-$ to total $\Lambda\pi^+\pi^-$ was thus obtained at each energy. Then the $K^-p\rightarrow\Lambda\pi^+\pi^-$ cross section [Fig. 1(b)] was modified by these ratios to obtain a $K^-p \rightarrow\Sigma^+(1385)\pi^-$ cross section free from interference and background [Fig. 1(c)], and similarly, $\Sigma^-(1385)$ production.

These cross sections were fitted by $\pi(\lambda/2\pi)^2 \times(J+\frac{1}{2})|T|^2$, where the amplitude T for the reaction was parametrized as

$$T=(a+bp^l)\exp[i(c+dp^l)] + (\Gamma_e\Gamma_r)^{1/2}/(E_0-E-\tfrac{1}{2}i\Gamma), \qquad (5)$$

with p^l the incident laboratory momentum and $E\equiv E_{\mathrm{c.m.}}$. The Γ's have the following forms:

$$\Gamma_e=0.225\Gamma_0 B_2(p)(p/E)[B_2(p_0)p_0/E_0]^{-1},$$
$$\Gamma_r=G_{1520}{}^2 B_0(\bar{p})\bar{p}M_N/E, \qquad (6)$$

where $\Gamma_0=16$ MeV, and $B_l(p)$ is the (Blatt-Weisskopf) centrifugal-barrier factor. $G_{1520}{}^2$ represents the coupling constant for the decay $\Lambda(1520)\rightarrow\Sigma(1385)\pi$; $\bar{p}$ represents the average momentum for the $\Sigma(1385)\pi$ in the $\Lambda(1520)$ rest frame at mass equal to E. In Eq. (5), Γ is the sum of $\bar{K}N$, $\Sigma\pi$, and $\Sigma(1385)\pi$ widths.

A value for $G_{1520}{}^2$ of 0.019 ± 0.003 [0.012 ± 0.0025] is obtained from fitting the $\Sigma^+(1385)\pi^-$ [$\Sigma^-(1385)\pi^+$] cross section. There are two different methods of calculating the mixing angle. Method I is to take

$$\sin^2\theta=G_{1520}{}^2/G_{8,10,8}{}^2=G_{1520}{}^2/c_{\Sigma\pi}{}^2 g_{8,10,8}{}^2.$$

Here the SU(3) coupling constant $g_{8,10,8}{}^2$ is extracted from branching ratios for $\Xi^*(1815)\rightarrow\Xi^*(1530)\pi$ and $N^*(1515)\rightarrow\Delta(1236)\pi$. Using $(30\pm15)\%$ and $(35\pm15)\%$ for these,[18] we find $g_{8,10,8}{}^2$ to be 0.29 ± 0.10 or $G_{8,10,8}{}^2=0.17\pm0.06$. Method I thus yields a mixing angle $|\theta|=17.0_{-3.0}^{+4.5}{}^\circ$.

Method II takes $\tan^2\theta=G_{1520}{}^2/G_{1690}{}^2$. Using an upper limit of $(25\pm4)\%$ for the decay $\Lambda(1690)\rightarrow\Sigma(1385)\pi$, we estimated the upper limit for $G_{1690}{}^2$ to be 0.072 ± 0.012.[3] Method II gives a lower limit on the mixing angle, $|\theta|>24.0\pm3.0^\circ$.

We estimate the $\Lambda(1520)\rightarrow\Sigma(1385)\pi$ branching ratio (all charge states) to be $(4.1\pm0.5)\%$. We point out that no $\Lambda(1520)\rightarrow\Lambda\pi^+\pi^-$ direct decay is found in our 2600-event sample, the only nonresonant-$\Lambda\pi$ amplitudes being $(SD)_{01}$ and $(SD)_{11}$. Our cross section for $K^-p\rightarrow\Lambda\pi^+\pi^-$ peaks at 3.2 mb[1]; of this, approximately 1.25 mb is attributable to $\Lambda(1520)\rightarrow\Sigma^\pm(1385)\pi^\mp$ and the remainder is background and interference effects. We believe that the $\Lambda(1520)\rightarrow$ (total $\Lambda\pi^+\pi^-$) branching ratio tabulated by the Particle Data Group and the $\Lambda(1520)\rightarrow$ (direct $\Lambda\pi^+\pi^-$) ratio from Burkhardt *et al.*[3] need re-examination; the data used for these suffered from very limited statistics and possibly from neglected interference problems.

These θ values are remarkably consistent with the θ obtained from the mass formula and from

$\underline{8}\times\underline{8}$ decays.[4-6] Various SU(3) symmetry-breaking models have been explored and compared with experimental $\underline{8}\times\underline{8}$ decay rates.[19,20] However, the apparent agreement among three types of mixing-angle estimates raises some question as to whether any mechanism beyond pure representation mixing is operative.[21]

We appreciate helpful discussions with Professor Robert D. Tripp, Dr. Ronald F. Peierls, and Professor J. David Jackson, and especially with Professor Eugene Golowich. We acknowledge the assistance of Professor William J. Willis, Professor S. Steven Yamamoto, Dr. David Berley, and Mr. Robert Ponte. We appreciate the aid of Professor Horace Taft and Mr. Peter Lucas and other PEPR personnel. We thank the BNL bubble-chamber and alternating gradient synchrotron crews; the University of Massachusetts, Yale, and BNL scanners; and the University of Massachusetts Research Computer Center personnel.

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

†Present address: Laboratoire Leprince-Ringuet, Ecole Polytechnique, Paris V^{e}, France.

[1]M. B. Watson, M. Ferro-Luzzi, and R. D. Tripp, Phys. Rev. 131, 2248 (1963).

[2]D. Cline, R. Laumann, and J. Mapp, Lett. Nuovo Cimento 2, 407 (1969).

[3]E. Burkhardt *et al.*, Nucl. Phys. B27, 64 (1971). See also R. Levi Setti, in *Proceedings of the Lund International Conference on Elementary Particles, Lund, Sweden, 1969,* edited by G. von Dardel (Berlingska Boktryckeriet, Lund, Sweden, 1970).

[4]G. B. Yodh, Phys. Rev. Lett. 18, 810 (1967); R. D. Tripp *et al.*, Nucl. Phys. B3, 10 (1967).

[5]N. Masuda and S. Mikamo, Phys. Rev. 162, 1517 (1967).

[6]R. D. Tripp, in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, Austria, 1968,* edited by J. Prentki and J. Stenberger (CERN Scientific Information Service, Geneva, Switzerland, 1968).

[7]The τ-decay information was obtained (through Mr. Peter Lucas) from three-prongs measured by the PEPR (precision encoding and pattern recognition) group at Yale University.

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

[9]M. Olsson and G. B. Yodh, Phys. Rev. Lett. 10, 353 (1963).

[10]B. Deler and G. Valladas, Nuovo Cimento 45A, 559 (1966); B. Sakita, Nuovo Cimento 22, 1113 (1961); J. M. Namyslowski *et al.*, Phys. Rev. 157, 1328 (1967).

[11]R. F. Peierls, BNL Report No. 9621, 1965 (unpublished).

[12]A. H. Rosenfeld and W. E. Humphrey, Annu. Rev. Nucl. Sci. 13, 127 (1963).

[13]N. Byers and S. Fenster, Phys. Rev. Lett. 11, 52 (1963).

[14]P. E. Schlein *et al.*, Phys. Rev. Lett. 11, 167 (1963); J. B. Shafer and D. O. Huwe, Phys. Rev. 134, B1372 (1964).

[15]J. Button-Shafer, Phys. Rev. 139, B607 (1965), and Phys. Rev. 150, 1308 (1966).

[16]R. H. Dalitz, Enrico Fermi Institute Report No. EFINS-61-69 (unpublished).

[17]S.-b. Chan, thesis, University of Massachusetts, 1970 (unpublished).

[18]A. Barbaro-Galtieri, private communication.

[19]E. Golowich, Phys. Rev. 177, 2295 (1969).

[20]J. J. Brehm and L. F. Cook, Phys. Rev. 187, 2174 (1969).

[21]E. Golowich, private communication.