§Present address: University of California, Santa Cruz, Calif.

[1]G. Belletini et al., Nucl. Phys. 79, 609 (1966).

[2]J. G. Asbury et al., Phys. Rev. Letters 19, 865 (1967); G. McClellan et al., Phys. Rev. Letters 22, 377 (1969); F. Bulos et al., Phys. Rev. Letters 22, 490 (1969).

[3]A. M. Boyarski et al., Phys. Rev. Letters 20, 300 (1968); 22, 1131 (1969).

[4]L. Stodolsky, Phys. Rev. Letters 18, 135 (1967); K. Gottfried and D. R. Yennie, Phys. Rev. 182, 1595 (1969); S. J. Brodsky and J. Pumplin, Phys. Rev. 182, 1794 (1969); M. Nauenberg, Phys. Rev. Letters 22, 556 (1969); B. Margolis and C. L. Tang, Nucl. Phys. B10, 329 (1969).

[5]Including the beryllium and carbon data increases the χ^2 considerably (the sum of the χ^2's from the four fits went from 15 for 6 degrees of freedom to 60 for 12 degrees of freedom). Since the beryllium and carbon points usually had the best statistics, the effect on the answer was large giving an average $w=0.62$.

[6]D. O. Caldwell, et al., in Proceedings of the Conference on Photon and Electron Interactions, Daresbury, England, 15-19 September 1969 (to be published); H. Meyer et al., ibid.

[7]G. McClellan et al., Phys. Rev. Letters 23, 554 (1969). This experiment was performed at $-t=0.1$ GeV^2 where correlations may have considerable effect; π^+ production, for example, is suppressed by a factor of 1.5 at this momentum transfer.

[8]W. Schmidt and D. R. Yennie, Phys. Rev. Letters 23, 623 (1969).

[9]A. M. Boyarski et al., Phys. Rev. Letters 21, 1767 (1968).

[10]O. Kofoed-Hansen and B. Margolis, Nucl. Phys. B11, 455 (1969).

[11]H. A. Bethe and P. J. Siemens, Phys. Letters 27B, 549 (1968).

[12]C. E. Wiegand, Phys. Rev. Letters 22, 1235 (1969).

[13]J. M. Eisenberg, Nucl. Phys. B3, 387 (1967).

STUDY OF THE REACTION $K^-n\rightarrow\Lambda\pi^-$ AT 3.9 AND 3.6 GeV/c: TEST OF EXCHANGE DEGENERACY IN THE t REGION AND AN OBSERVATION OF A BACKWARD PEAK IN THE u REGION*

David J. Crennell, Uri Karshon, † Kwan Wu Lai, John S. O'Neall, ‡ and J. Michael Scarr
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

and

Robert M. Lea, Thomas G. Schumann, and Ernest M. Urvater
Department of Physics, City College of the City University of New York, New York, New York

(Received 6 October 1969)

Angular distributions in the low-$|t|$ region in the reaction $K^-n\rightarrow\Lambda\pi^-$ and in the line-reversed reaction $\pi^-p\rightarrow\Lambda K^0$ and from other complementary experiments do not support the predictions of exchange degeneracy between the $K_{1/2}^*(890)$ and the $K_{1/2}^*(1420)$ up to $s\sim 11$ GeV^2. In the low-$|u|$ region of the reaction $K^-n\rightarrow\Lambda\pi^-$ at 3.9 GeV/c, we observe a peak with a slope of 10 ± 3 GeV^{-2} followed by a valley from $u=-0.15$ to -0.4 GeV^2. A simple Regge-pole fit to this backward-scattering region using the N_α trajectory is presented.

The purpose of this Letter is to present (I) an experimental test of the idea of exchange degeneracy between the $K_{1/2}^*(890)$ and the $K_{1/2}^*(1420)$ trajectories from the reaction $K^-n\rightarrow\Lambda\pi^-$ and the line-reversed reaction $\pi^-p\rightarrow\Lambda K^0$, and (II) an observation of a backward peak followed by a valley from $u=-0.15$ to -0.4 GeV^2 in the reaction $K^-n\rightarrow\Lambda\pi^-$ at 3.9 GeV/c.

The $K^-n\rightarrow\Lambda\pi^-$ data at 3.9 and 3.6 GeV/c come from an exposure of K^- mesons in the Brookhaven National Laboratory 80-in. deuterium-filled bubble chamber. Approximately 240 000 pictures were analyzed to yield 917 events at 3.9 GeV/c and 239 events at 3.6 GeV/c in this reaction.[1] Figure 1 is the distribution in cosine of the angle between the incident K^- and the outgoing π^- in the total c.m. system at 3.9 GeV/c. A strong forward ($\hat{K}^-\cdot\hat{\pi}^-\approx+1$) peak as well as a pronounced backward ($\hat{K}^-\cdot\hat{\pi}^-\approx-1$) peak are evident. We shall first consider the forward scattering, and then the backward scattering.

(I) Forward scattering.– For small values of four-momentum transfer squared (t) between incident K^- and outgoing π^-, the $K^-n\rightarrow\Lambda\pi^-$ amplitude is expected to be dominated by the exchange of the $K_{1/2}^*(890)$ trajectory (odd-signature factor) and the $K_{1/2}^*(1420)$ trajectory (even-signature factor). According to Regge-pole theory,[2] the s-channel amplitude A_+ for $K^-n\rightarrow\Lambda\pi^-$ and the u-channel or line-reversed amplitude A_- for $\pi^+n\rightarrow\Lambda K^+$ (or $\pi^-p\rightarrow\Lambda K^0$ via charge symmetry) can be written for small t as

$$A_\pm(s,t)=\beta_1(s,t)\,(1+e^{-i\pi\alpha_1(t)})\pm\beta_2(s,t)(1-e^{-i\pi\alpha_2(t)}),\qquad(1)$$

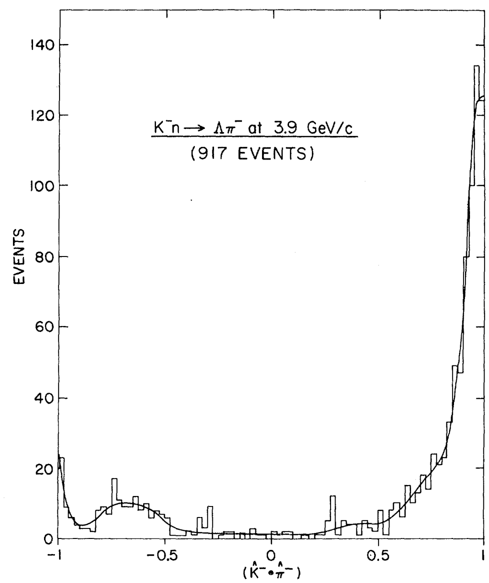

FIG. 1. C.m. angular distribution. Solid line is the polynomial fit to the data.

where α_1 (α_2) refers to the positive-signature $K_{1/2}^*(1420)$ trajectory [negative-signature $K_{1/2}^*(890)$ trajectory], and the β's are real. From the hypothesis of duality applied to $K\pi$ scattering and the apparent lack of experimental evidence for $I=\frac{3}{2}$ K^* resonances, the $K_{1/2}^*(890)$ and $K_{1/2}^*(1420)$ trajectories are exchange degenerate.[3] The "weak" form of exchange degeneracy[4] states that $\alpha_1(t)=\alpha_2(t)$, and from Eq. (1) one obtains

$$|A_+| = |A_-| \text{ or } d\sigma_+/dt = d\sigma_-/dt, \quad (2)$$

valid for large total c.m. energy squared (s) and small $|t|$. Figure 2(a) is the differential cross section for the reaction $K^-n \to \Lambda\pi^-$ at 3.9 GeV/c from this experiment. Events with $0.05 < |t| < 0.45$ GeV^2 were fitted with $\sim e^{bt}$. Values of $b = 4.2 \pm 0.5$ and 3.5 ± 0.9 GeV^{-2} were obtained[5] for this reaction at 3.9 GeV/c [shown in Fig. 2 (a)] and 3.6 GeV/c (not shown), respectively. The value of b does not have a strong energy dependence for this reaction[6] and for the reaction $K^-p \to \Lambda\pi^0$.[7] The weighted average of b is 4.0 ± 0.6 GeV^{-2} from $s \approx 5$ to 11 GeV^2. This is illustrated in Fig. 3. The values of b for the corresponding line-reversed or u-channel reaction $\pi^-p \to \Lambda K^0$ in the region $|t| < 0.4$ GeV^2 are shown in Fig. 3 for the purpose of comparison.[8] We note that the weighted average value of b for this u-channel reaction is 7.3 ± 0.8 GeV^{-2}. Experimentally, the values of b for $\pi^-p \to \Lambda K^0$, $\Sigma^0 K^0$, as well as Y^0K^0 are similar in the energy

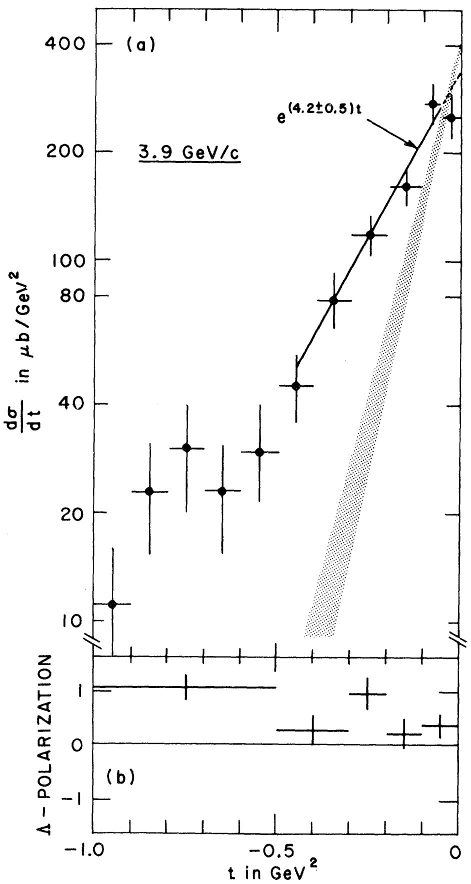

FIG. 2. (a) Differential cross section in the forward region. Solid line is an exponential fit to the data from $0.05 < |t| < 0.45$ GeV^2. The shaded area, presented for the purpose of comparison, shows the slope and its error for the differential cross section of the line-reversed reaction, $\pi^-p \to \Lambda K^0$, at ~4 GeV/c (Ref. 8). See text for details. (b) Λ polarization in the forward region.

region where the separation of Λ and Σ^0 is possible.[9] In the higher energy region, only combined data are available, namely $\pi^-p \to Y^0K^0$ where Y^0 includes both Σ^0 and Λ. We present some of these higher energy points[10] in Fig. 3 for this comparison assuming that the values of b for $\pi^-p \to \Lambda K^0$ and Y^0K^0 are similar (as observed in the lower energy region). The weighted average value of b for the reactions $\pi^-p \to Y^0K^0$ is 7.8 ± 0.9 GeV^{-2}. The difference between the weighted average values of b for the $K^-N \to \Lambda\pi$ (4.0 ± 0.6 GeV^{-2}) and $\pi^-p \to \Lambda K^0$ (7.3 ± 0.8 GeV^{-2}) is significant; and it may suggest that the prediction of the "weak" form of exchange degeneracy does not agree well with experimental data in these reactions in this energy region. However, this difference can be due to any of the following:

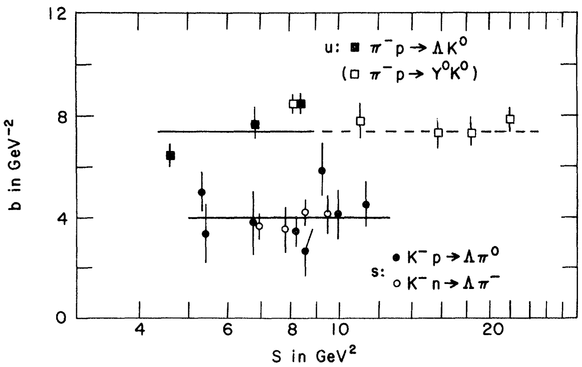

FIG. 3. A compilation of the values of slope for $K^-n \to \Lambda\pi^-$ or $K^-p \to \Lambda\pi^0$ and $\pi^-p \to \Lambda K^0$ or $\pi^-p \to Y^0K^0$ as a function of total c.m. energy squared. Solid lines are weighted averages of b for the s channel ($\langle b\rangle = 4.0 \pm 0.6$ GeV^{-2}) and for the u channel ($\langle b\rangle = 7.3 \pm 0.8$ GeV^{-2}). Dashed line is an extension of $\langle b\rangle$ for the u channel to higher s values.

(i) The process is not dominated by K^* and K^{**} exchanges alone for $s \approx 5$ to 11 GeV^2 where this comparison is made; (ii) the contribution from absorption in the low-$|t|$ region for these two reactions can be different[11]; (iii) there possibly exist exotic states which can "break" the prediction of exchange degeneracy from duality. Furthermore, the "strong" form of exchange degeneracy demands $\alpha_1 = \alpha_2$ and $\beta_1 = \beta_2$. Therefore, it predicts zero Λ polarization for all relevant t. This feature is not observed in Fig. 2(b). In fact, the values of Λ polarization are large at some t values and positive up to $-t \approx 1$ GeV^2.[12]

(II) Backward scattering.—Backward scattering in the reaction $K^-n \to \Lambda\pi^-$ should be dominated by isospin-$\frac{1}{2}$ baryon exchange alone, namely the N_α (the $J^P = \frac{1}{2}^+$ nucleon trajectory) and possibly N_γ (the $J^P = \frac{1}{2}^-$ nucleon trajectory). A sharp dip in $d\sigma/du$, where $u = (P_\Lambda - P_{K^-})^2$, is expected from the Regge-pole theory for a single N_α trajectory assumption when $\mathrm{Re}\,\alpha_{N_\alpha}$ goes through the nonsense, wrong-signature value of $-\frac{1}{2}$. In the 3.9-GeV/c experiment, we observe a backward peak with a slope of 10 ± 3 GeV^{-2} (the fit is not shown) followed by a somewhat broad valley from $u = -0.14$ to -0.4 GeV^2. It then reaches a second maximum at $u = -0.8$ GeV^2 [see Fig. 4(a)]. The Λ polarization is shown in Fig. 4(b). A single N_α-trajectory fit with both spin-flip and spin-nonflip amplitudes[13] is made in the backward region (to $u = -1.5$ GeV^2). The best fit to the data [the solid line in Fig. 4(a)] from the maximum-likelihood method suggests that the spin-flip term is dominant.[14] The general feature of a backward peak and dip is also observed in the reaction $\pi^+p \to p\pi^+$ (with sharper dip at $u \approx -0.14$ GeV^2).[15] It is important to note that in the backward $\pi^+p \to p\pi^+$ scattering, the Δ_δ as well as N_α and N_γ trajectories are present whereas in our reaction possible complications due to Δ_δ are not present. Behavior of the backward scattering from the reaction $K^-n \to \Lambda\pi^-$ should thus be considered together with other existing data from πN, γN, etc. in order to perform a more complete analysis of the N_α, N_γ, and Δ_δ trajectories.

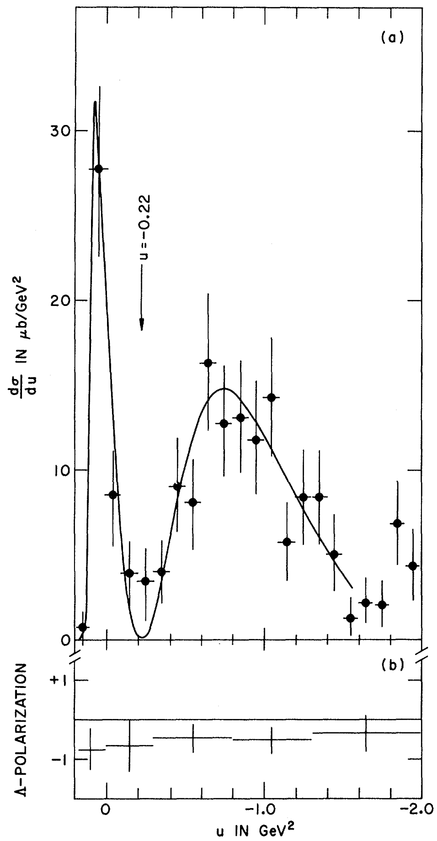

FIG. 4. (a) Differential cross section in the backward region. Solid line is a single-Regge-trajectory (N_α) fit to the data for $u \geq -1.5$ GeV^2. See text for details. (b) Λ polarization in the backward region.

In summary, we have observed a possible deviation from the prediction of exchange degeneracy of the $K_{1/2}^*(890)$ and the $K_{1/2}^*(1420)$ in the reaction $K^-N \to \Lambda\pi$ and the line-reversed reaction $\pi^-p \to \Lambda K^0$ in the energy range $s \approx 5$ to 11 GeV^2. Further experimental tests are desirable when higher energy data become available. In addition, we have also observed a backward peak in the $K^-n \to \Lambda\pi^-$ reaction at 3.9 GeV/c.

We wish to acknowledge useful discussions with F. Hayot, B. Kayser, and C. C. Shih concerning the backward peaks, and to thank J. Kirz and Y. Zarmi for their enthusiastic interest. We also want to express our appreciation to our colleagues D. Bassano, R. L. Eisner, G. R. Kalbfleisch, D. D. Reeder, and N. P. Samios, for making their unpublished data available to us for the purpose of this comparison. Finally, it is a pleasure to thank R. P. Shutt for his continued interest and encouragement.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission. The work at City College was partially supported by the National Science Foundation.

†Present address: Weizmann Institute of Science, Rehovoth, Israel.

‡Present address: Collège de France, Paris, France.

[1]For details of analysis, see for example, D. J. Crennell et al., Phys. Rev. Letters 22, 1398 (1969), and 21, 648 (1968). The cross contamination between the $\Lambda\pi^-$ and $\Sigma^0\pi^-$ channels for the reaction is estimated to be about 10% in the forward-scattering region.

[2]See for example, D. D. Reeder and K. V. L. Sarma, Phys. Rev. 172, 1566 (1968).

[3]For earlier work on exchange degeneracy see for example R. C. Arnold, Phys. Rev. Letters 14, 657 (1965); A. Ahmadzadeh, Phys. Letters 22, 669 (1966).

[4]F. J. Gilman, Phys. Letters 29B, 673 (1969).

[5]The lower limit, 0.05 GeV^2, was used for the fit to avoid the unreliable correction due to the severe scanning bias. The upper limit, 0.45 GeV^2, was used for this reaction because the line-reversed reaction has a sharp change of slope at $|t| \sim 0.45$ GeV^2.

[6]For example: $b = 3.6 \pm 0.5$ at 3.0 GeV/c [R. Barloutaud et al., Nucl. Phys. B9, 493 (1969)]; $b = 4.1 \pm 0.8$ at 4.5 GeV/c [W. L. Yen et al., Phys. Rev. Letters 22, 963 (1969)].

[7]For example: $b = 5 \pm 1.7$ at 2 GeV/c (G. R. Kalbfleisch, private communication); $b = 3.4 \pm 1.1$ at 2.24 GeV/c [G. W. London et al., Phys. Rev. 143, 1034 (1966)]; $b = 3.8 \pm 1.1$ at 3 GeV/c; [Ecole Polytechnique–Saclay–Amsterdam Collaboration, in Proceedings of the Twelfth International Conference on High Energy Physics, Dubna, U.S.S.R., 1964 (Atomizdat., Moscow, U.S.S.R., 1966), p. 650; and Cambridge Electron Accelerator Report, 1966 (unpublished)]; $b = 3.3 \pm 0.6$ at 3.5 GeV/c [Birmingham-Glasgow-London (I.C.)-Oxford-Rutherford Collaboration, Phys. Rev. 152, 1148 (1966)]; $b = 2.7 \pm 1.1$ at 3.9 GeV/c and $b = 4.1 \pm 1.1$ at 4.65 GeV/c (D. Bassano, R. I. Eisner, and N. P. Samios, private communications); $b = 5.9 \pm 1.1$ at 4.1 GeV/c and $b = 4.6 \pm 1.0$ at 5.5 GeV/c (D. D. Reeder, private communications). The $\Sigma^0\pi^0$ contamination in the forward-scattering region is ~5% or less in this energy region and cannot change the value of b for $K^-p \to \Lambda\pi^0$ by more than the quoted errors.

[8]O. I. Dahl et al., Phys. Rev. 163, 1430 (1967).

[9]Experimentally, we note b is 6.4 ± 0.5 for $\pi^-p \to \Lambda K^0$ and 7.5 ± 1.0 for $\pi^-p \to \Sigma^0 K^0$ at ~2 GeV/c; 9.9 ± 1.1 and 6.3 ± 2.9 at ~4 GeV/c where experimental separation of Σ^0 and Λ^0 is possible (see Ref. 8). In fact, the value of b from a $\pi^-p \to Y^0K^0$ experiment at 4 GeV/c is 8.57 ± 0.38 GeV^{-2} [T. F. Hoang et al., Phys. Letters 25B, 615 (1967)]. Furthermore, this similarity seems also to exist in the $K^-n \to \Lambda\pi$ and $K^-n \to \Sigma^0\pi^-$ reactions. For example, the value of b is 3.6 ± 0.5 for $K^-n \to \Lambda\pi^-$ and 5.4 ± 0.4 for $K^-n \to \Sigma^0\pi^-$ at 3 GeV/c; 3.5 ± 0.9 and 4.1 ± 2.0 at 3.6 GeV/c; 4.2 ± 0.5 and 5.5 ± 2.0 at 3.9 GeV/c; 4.1 ± 0.8 and 5.1 ± 0.2 at 4.5 GeV/c (see Ref. 6 and this experiment).

[10]D. J. Crennell et al., Phys. Rev. Letters 18, 86 (1967); B. Bertolucci et al., Lettere Nuovo Cimento 2, 149 (1969).

[11]See for instance C. Michael, "Exchange Degeneracy, Duality, and Regge Cuts" (to be published).

[12]This result is not unexpected. The strong form of exchange degeneracy is not imposed here by the duality hypothesis because of the lack of exotic channels in this reaction. However, according to the "duality diagram" approach of H. Harari [Phys. Rev. Letters 22, 562 (1969)] and J. Rosner [Phys. Rev. Letters 22, 689 (1969)], the Λ polarization should be approximately zero in the negative-t region for this reaction because the diagram corresponding to this reaction is an "illegal." In fact, experimentally the Λ polarization is large and positive at 3 GeV/c (Barloutaud et al., Ref. 6), 3.6 and 3.9 GeV/c (this experiment), and 4.5 GeV/c (Yen et al., Ref. 6).

[13]We folded our experimental resolution function into the expression for the cross section $d\sigma/du = \text{const} \times [|M_{++}|^2 + |M_{+-}|^2]$, where

$$M_{++} = \gamma \frac{(-u+u_0)^{1/2}}{M_n}\left(\alpha + \frac{1}{2}\right)\frac{1+e^{-i\pi(\alpha-\frac{1}{2})}}{\cos(\pi\alpha)\Gamma(\alpha+\frac{3}{2})} \times \left(\frac{s}{s}\right)_0 \alpha_0 + \alpha'(u-u_0),$$

the spin-flip term, and

$$M_{+-} = [AM_n/(-u+u_0)^{1/2}]M_{++},$$

the spin-nonflip term. A is a parameter, u_0 is the maximum allowed value of u, γ is a constant, $\alpha = \alpha_0 + \alpha' u$ where α_0 and α' are parameters in the fit, s_0 is taken to be 0.5 GeV^2, and M_n is the nucleon mass [private communication from F. Hayot; and see, for example, V. Barger and D. Cline, Phys. Rev. 155, 1792 (1969)]. For general Regge descriptions of the backward peaks, see, for example, C. B. Chiu and J. D. Stack, Phys. Rev. 153, 1575 (1967).

[14]$A^2 = |M_{+-}|^2/|M_{++}|^2 = 0.07 \pm 0.03$, $\alpha_0 = -0.34 \pm 0.01$, and $\alpha' = 0.73 \pm 0.02$ are the results of the best fit to our data.

[15]See for example, J. P. Chandler et al., Phys. Rev. Letters 23, 186 (1969), and J. Orear et al., Phys. Rev. Letters 21, 389 (1968).