[1]For a list of theoretical and experimental papers on the one-pion exchange model, see, e. g., E. Ferrari and F. Selleri, Suppl. Nuovo Cimento 24, 453 (1962).

[2]Throughout this paper, $N_{3/2}^*$, Y_1^*, and K^* stand, respectively, for the 3-3 resonance, the 1380-MeV π-Λ resonance, and the 885-MeV K-π resonance. The term "isobar" stands for $N_{3/2}^*$ or Y_1^*.

[3]For vector meson exchange in processes like $\pi^- + p \rightarrow K^* + \Sigma$, see G. A. Smith et al., Phys. Rev. Letters 10, 138 (1963).

[4]To prove this, just observe that $k_\mu v_\mu = 0$ for (1a) and (1b) and $k_\mu v_\mu = \pm(m_K^2 - m_\pi^2)(m_V^2 - \Delta^2)/m_V^2$ for (1c) and (1d).

[5]R. H. Dalitz and D. R. Yennie, Phys. Rev. 105, 1598 (1957).

[6]See, e. g., W. S. McDonald, V. Z. Peterson, and D. R. Corson, Phys. Rev. 107, 577 (1957).

[7]The dominance of $M1 \rightarrow p_{3/2}$ is expected on theoretical grounds: G. F. Chew and F. E. Low, Phys. Rev. 101, 1579 (1956); G. F. Chew, M. L. Goldberger, F. E. Low, and Y. Nambu, Phys. Rev. 106, 1345 (1957); S. Fubini, Y. Nambu, and V. Wataghin, Phys. Rev. 111, 329 (1958).

[8]J. J. Sakurai, Ann. Phys. (N. Y.) 11, 1 (1960).

[9]M. Gell-Mann and F. Zachariasen, Phys. Rev. 124, 953 (1961).

[10]The proportionality constant in this case is (3/2) $\times (f_\rho/e)$, where $f_\rho^2/4\pi = 4\gamma^2/4\pi \approx 2.0$, $e^2/4\pi = 1/137$. We will discuss a quantitative test of the "ρ-photon analogy" in a separate communication.

[11]M. Gell-Mann, Phys. Rev. 111, 362 (1958).

[12]M. Gell-Mann, Phys. Rev. 125, 1067 (1962); Y. Ne'eman, Nucl. Phys. 26, 222 (1961).

[13]For the unitary spin assignment of low-lying isobars, see R. E. Behrends et al., Rev. Mod. Phys. 34, 1 (1962); S. H. Glashow and J. J. Sakurai, Nuovo Cimento 25, 337 (1962); S. H. Glashow and J. J. Sakurai, Nuovo Cimento 26, 622 (1962).

[14]L. Bertanza et al., Phys. Rev. Letters 10, 176 (1963).

[15]S. S. Yamamoto (private communication).

[16]B. Kehoe, following Letter [Phys. Rev. Letters 11, 93 (1963)].

[17]R. K. Adair, Phys. Rev. 100, 1540 (1955).

[18]The Adair method is known to fail not only in (1b), (1c), and (1d), but also in (1a) [D. Stonehill, Ph. D. thesis, Yale University, 1962 (unpublished)]. On the other hand, the Adair method has been successfully applied to $N_{3/2}^*$ decay in $\pi^- + p \rightarrow N_{3/2}^{*-} + \pi^+$ [V. Alles-Borelli et al., Nuovo Cimento 14, 211 (1959)]; note, however, that one-ρ exchange is forbidden in this reaction. It is worth remarking that at higher energies ($\sim$3.3 BeV/c), the reaction $\pi^- p \rightarrow N_{3/2}^{*-}\pi^+$ does not occur, whereas the reaction $\pi^- p \rightarrow N_{3/2}^{*-}\pi^-$ is observed [Z. G. T. Guiragossian, Phys. Rev. Letters 11, 85 (1963)] in agreement with dominant ρ exchange.

[19]The relevant Clebsch-Gordan coefficients may be found in reference 13. The relation $\sigma(a)/\sigma(b) = 2$ follows from the assumption that the ρ is coupled universally to the isospin current; the relation $\sigma(c) = \sigma(d)$ is a consequence of any model based on K^* exchange. Our relations should not be confused with Eq. (5b) of S. Meshkov, C. A. Levinson, and H. J. Lipkin [Phys. Rev. Letters 10, 361 (1963)] which follows from unitary symmetry alone.

[20]R. D. Tripp, M. B. Watson, and M. Ferro-Luzzi, Phys. Rev. Letters 8, 175 (1962).

[21]S. B. Treiman and C. N. Yang, Phys. Rev. Letters 8, 140 (1962).

[22]The Treiman-Yang distribution for the $M1 \rightarrow p_{3/2}$ case must be of the form $1 + 2\sin^2\varphi$. A correlation of this kind has been reported by S. Goldhaber et al. [Bull. Am. Phys. Soc. 8, 20 (1963); Proceedings of the Conference on Fundamental Particle Resonances, Ohio University, Athens, Ohio (to be published)] in the reaction $K^+ + p \rightarrow K^\circ + N_{3/2}^{*++}$ at 1.96 BeV/c.

ISOBAR PRODUCTION BY 910-MeV/c K^+ MESONS*

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(Received 29 May 1963)

In an accompanying Letter by Stodolsky and Sakurai,[1] a model for isobar production by vector meson exchange is presented. In this Letter the predictions of that model are compared to the results of an experimental investigation of the process

$$K^+ + p \rightarrow K^0 + p + \pi^+. \qquad (1)$$

The model assumes that the final-state π^+ and proton are the decay products of the $J = 3/2$, $I = 3/2$ nucleon isobar which was produced by the exchange of a ρ meson.

The events were found in a scan of 40 000 pictures from an exposure of the Berkeley 30-in. propane bubble chamber to a separated beam of K^+ mesons. The beam momentum, over the run, was distributed about 910 MeV/c with a variance of approximately 40 MeV/c. Only those events were considered which had associated with them the decay of the K^0 via the charged K_1^0 mode:

$$K_1^0 \rightarrow \pi^+ + \pi^-. \qquad (2)$$

Candidates found in the scan were measured on standard digitized equipment and analyzed in the

FOG-CLOUDY-FAIR program sequence. Each was constrained to the hypothesis that the production interaction, (1), took place on a free proton. Contamination of the production events, by the same process on a proton bound in carbon, was estimated to be $4.0 \pm 1.5\%$ from the observed tail in the chi-square distribution. The chi-square distribution from carbon events constrained to the free-proton hypothesis was shown, by Monte Carlo simulation, to be flat in the region $0 < \chi^2 < 50$.

Tau decays of the beam particles,

$$K^+ \to \pi^+ + \pi^+ + \pi^-, \tag{3}$$

were also selected in the scan. They were measured and analyzed for the determination of K^+ track length and beam selection criteria. Each event was constrained to the tau decay hypothesis, (3). The distribution of dip stretches for the K^+ and the pions, taken separately, were quite asymmetric. Analysis of the reconstruction process indicated the probable cause to be an incorrectly determined optical constant. Corrections to remove the effect of this error were made on the unconstrained track data of every tau decay and production candidate. Each event was then constrained using GUTS. The corrected data produced excellent stretch and chi-square distributions.

The data were examined for possible systematic losses in the event selection. The only bias of any significance appeared to be against events with charged tracks which interacted very near the vertex from which they originated. The indicated loss was $2.5 + 1.0\%$ of the production events and $2.0 + 0.7\%$ of the tau decays. Scanning efficiency was determined to be $93.0 + 2.0\%$ and $95.8 + 1.0\%$ for the two event types from a rescan of 45% of the film. The indicated K^+ track length was $(8.19 + 0.47) \times 10^6$ cm which gave rise to 261 ± 19 production events with associated charged $K_1{}^\circ$ decays. The cross section for Reaction (1) is $2.10 + 0.20$ mb assuming that the K^0 decays to charged pions, (2), with a branching ratio of 1/3.

A completely general form for the differential cross section for the production process (1) is

$$d\sigma \propto (1/IwE)(d^3q'/w')\delta^4(q' + t - q - p) \times d^4t\,\delta(t^2 - m^2)dm^2B, \tag{4}$$

where

$$B = (d^3k/\epsilon)(d^3p'/E')\delta^4(t - k - p')\,|T|^2 \tag{5}$$

is a Lorentz-invariant function. The quantities $(\vec{q}, w)$, $(\vec{q}', w')$, $(\vec{p}, E)$, $(\vec{p}', E')$, and $(\vec{k}, \epsilon)$ are the four-momenta of the K^+, the K^0, the incoming and outgoing proton, and the π^+, respectively. The four-momentum of the combined π^+p system, t_μ, is given by

$$t_\mu = p_\mu' + k_\mu. \tag{6}$$

Bergia, Bonsignori, and Stanghellini[2] have discussed the effects of isobar formation in inelastic processes, using the above formalism. They suggest that the function B, evaluated in the rest frame of the π^+p system, the isobar rest frame, is given by

$$B = d\Omega_{\bar{q}}(\bar{q}/m)[\Gamma(m)/D^2(m)]\,|R|^2, \tag{7}$$

where $\bar{q}$ is the momentum of either the π^+ or proton, m is the mass of the π^+p system,

$$\Gamma(m) = 0.22\,\bar{q}^2/M_\pi(m - M_p), \tag{8}$$

and

$$D^2(m) = (m - m_0)^2 + \bar{q}^2\Gamma^2(m), \tag{9}$$

with $m_0 = 1238$ MeV. $|R|^2$ is the square of the portion of the matrix element which describes the production of the isobar.

The ρ-exchange model of Stodolsky and Sakurai, assuming a magnetic dipole interaction, predicts that

$$|R|^2 = [(\vec{q} \times \vec{q}')^2/(\Delta^2 - M_p{}^2)^2](1 + 3\cos^2\theta), \tag{10}$$

where $\Delta^2 = (w - w')^2 - (\vec{q} - \vec{q}')^2$ is the square of the four-momentum transfer, $\cos\theta = \hat{k}\cdot\hat{n}$, and $\hat{n} = (\vec{q} \times \vec{q}')/|\vec{q} \times \vec{q}'|$. In this expression for $|R|^2$, all vectors are to be evaluated in the isobar rest frame.

Figures 1, 2, and 3 show distributions based on all of the 218 production events which were in a predetermined fiducial volume and which satisfied selection criteria on chi-square and beam momentum and direction. The predictions of the model are shown as smooth curves. In Figs. 2 and 3, the theoretical distributions were averaged over the observed spread in barycentric energy.

Figure 1 presents the observed decay angular distribution for the isobar, relative to the production normal, $\hat{n}$. It is compared to the $(1 + 3\cos^2\theta)$ form predicted. The decay was also found to be aximuthally isotropic about $\hat{n}$. The equivalent of the Trieman-Yang test suggested by Stodolosky and Sakurai involves the distribu-

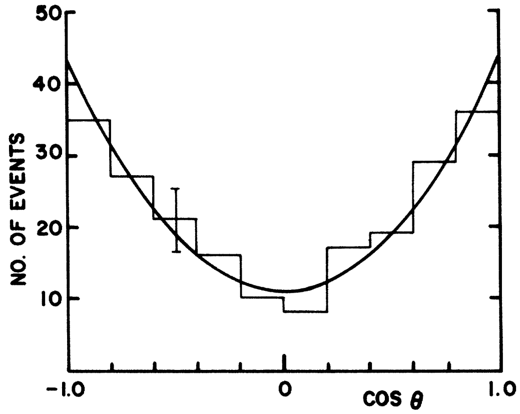

FIG. 1. Distribution of cos θ. The angle θ is the decay colatitude of the isobar with respect to the normal to the production plane, $\hat{n}$. Thus cos $\theta = \hat{k}\cdot\hat{n}$ evaluated in the isobar rest frame.

tion of the angle φ, where

$$\cos\varphi = \frac{\hat{n}\cdot[(\vec{q}-\vec{q}\,')\times\vec{k}]}{|(\vec{q}-\vec{q}\,')\times\vec{k}|}. \tag{11}$$

As in expression (10), $\vec{q}, \vec{q}\,'$, and $\vec{k}$ are evaluated in the isobar rest frame. For vector meson exchange φ should be distributed as $A + B\cos\varphi + C\cos^2\varphi$; for the particular interaction assumed here, $B/A = 0$ and $C/A = -0.67$. A least-squares fit to the data indicated

$$B/A = +0.10 \pm 0.20,$$

$$C/A = -0.57 \pm 0.20.$$

The chi-square fit of the observed distribution in φ to the predicted distribution was better than 65%.

Figures 2(a), 2(b), and 2(c) display the distributions of the cosines between the beam direction and the K^0, the π^+, and the proton, respectively, evaluated in the over-all center-of-mass system. While the peaking of the $\cos\Theta_{K^0}$ distributions depends upon the mass of the exchanged particle, through the propagator in Eq. (5), the quality of the fit to the theory is essentially constant for masses between 550 and 850 MeV.

The Q-value (effective mass less rest mass) distributions for the (π^+,p), the (K^0,p), and the (π^+,K^0) pairs are shown in Figs. 3(a), 3(b), and 3(c), respectively. The distributions predicted by phase space alone $[|T|^2 = \text{constant in Eq. (5)}]$ are shown by the dashed curves. The (π^+,K^0) Q distribution, Fig. 3(c), is consistent with phase space, the other two are not. Note that while the 883-MeV K^* is forbidden by energy

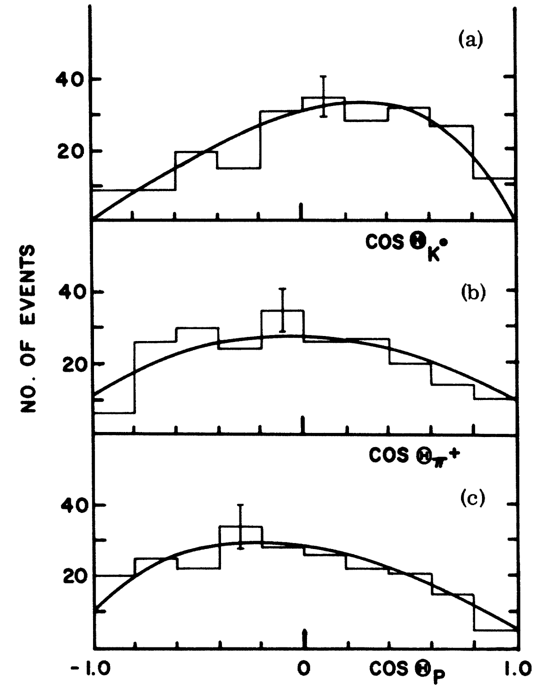

FIG. 2. Center-of-mass angular distributions for the three final-state particles, (a) the K^0, (b) the π^+, and (c) the proton. Displayed is the cosine of the angle between the particle and the beam direction.

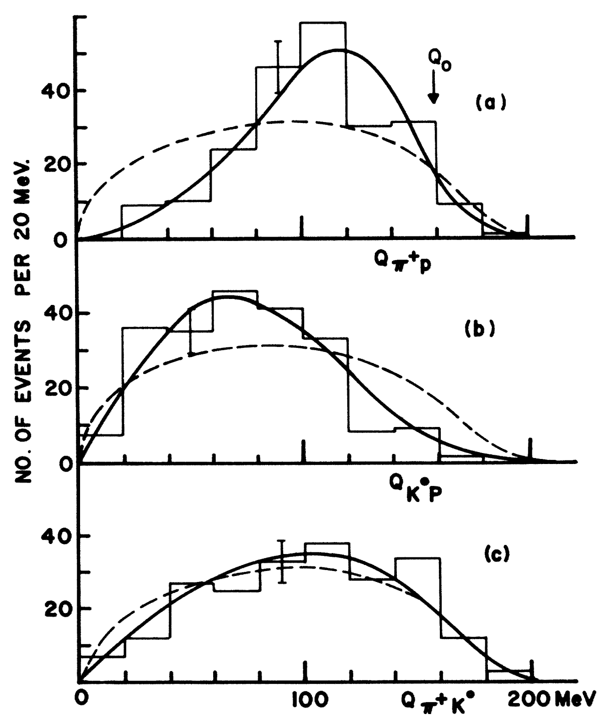

FIG. 3. Distribution of Q values for (a) the (π^+, p) system, (b) the (K^0,p) system, and (c) the (π^+,K^0) system.

conservation, the recently observed π-K resonance[3] at 723 MeV might be expected to appear at $Q = 85$ MeV. The data are consistent with no formation of this resonance. The value Q_0, corresponding to $m = m_0$, is indicated by the arrow on the (π^+, p) Q distribution, Fig. 3(a). The shift of the theoretical peak from this value represents the combined effects of phase space and the factor $(\vec{q}')^2$ in expression (10). For fixed barycentric energy, high isobar mass corresponds to low center-of-mass momentum of the K^0.

Much of the work was carried out at the University of Wisconsin under the very stimulating guidance of Professor Ugo Camerini and Professor W. F. Fry. The author would like to thank Professor Wilson Powell for making the film available and Howard White for overseeing most of the measurement and analysis. He would also like to acknowledge many helpful discussions with Dr. James Gaidos, Professor J. J. Sakurai, Professor George Snow, Professor Joseph Sucher, and Professor Leo Stodolsky.

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*Work supported by the U. S. Atomic Energy Commission and the Wisconsin Alumni Research Foundation.

†National Science Foundation Cooperative Fellow, 1959-1961.

[1] Leo Stodolsky and J. J. Sakurai, preceding Letter [Phys. Rev. Letters 11, 90 (1963)].

[2] S. Bergia, F. Bonsignori, and A. Stanghellini, Nuovo Cimento 16, 1073 (1960).

[3] G. Alexander, G. R. Kalbfleisch, D. H. Miller, and G. A. Smith, Phys. Rev. Letters 8, 447 (1962).

STRUCTURE OF THE WEAK INTERACTION $\Lambda + N \to N + N$

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In this Letter, the empirical evidence available on the nonmesonic decay of Λ hypernuclei will be analyzed in terms of the spin and isospin dependence of the weak interactions

$$\Lambda + p \to n + p, \tag{1}$$

$$\Lambda + n \to n + n. \tag{2}$$

Recently, measurements on the nonmesonic decay processes of ${}_\Lambda H^4$ and ${}_\Lambda He^4$ hypernuclei produced in K^--He^4 reactions have been reported by Block et al.[1] For ${}_\Lambda He^4$, they have obtained $Q({}_\Lambda He^5) = 0.52 \pm 0.10$ and $C({}_\Lambda He^4) = 2.2 \pm 0.8$, where Q denotes the ratio of nonmesonic to π^- decay modes and C denotes the ratio of Reactions (1) to (2), determined from the energy spectrum of the final-state protons. For ${}_\Lambda H^4$, they have obtained $Q({}_\Lambda H^4) = 0.26 \pm 0.13$. Using theoretical estimates[2] for the π^--mesonic decay rates, we may deduce the nonmesonic decay rates for these hypernuclei,

$$\Gamma_{nm}({}_\Lambda He^4) = (0.14 \pm 0.03)\Gamma_\Lambda, \tag{3a}$$

$$\Gamma_{nm}({}_\Lambda H^4) = (0.29 \pm 0.14)\Gamma_\Lambda, \tag{3b}$$

where $\Gamma_\Lambda = \tau_\Lambda^{-1} = (4.25 \pm 0.1) \times 10^9\ \mathrm{sec}^{-1}$ denotes the free Λ decay rate.[3] We note first that these rates are just compatible with the inequality

$$\Gamma_{nm}({}_\Lambda H^4) \leq 2\Gamma_{nm}({}_\Lambda He^4) \tag{4}$$

required by the $\Delta I = \frac{1}{2}$ rule.[4]

We shall base our detailed analysis on a simplified calculation[2] for the nonmesonic decay rates, which treats the Λ de-excitation by different nucleons as incoherent. This procedure neglects final-state interactions for the two fast outgoing nucleons, and neglects the interference effects which usually arise from antisymmetrization of the final state, corrections which are not expected to be important here, because of the large energy release. In this model, these rates are expressed in terms of the elementary rates R_{NS} for nonmesonic de-excitation of a ΛN system with total spin S, for unit density of nucleon N at the Λ position. In light hypernuclei, the initial ΛN states are S-wave, ${}^1S_0$ and ${}^3S_1$. The $\Lambda N \to NN$ transitions then possible are listed in Table I, together with the spin dependence of their corresponding matrix