Electronics and Atomic Collisions, London, 1963 (North-Holland Publishing Co., Amsterdam, 1964).
[5]R. Damburg and M. Gailitis, Proc. Phys. Soc. (London) 82, 1068 (1963).
[6]J. Arol Simpson, Rev. Sci. Instr. 32, 1283 (1961).
[7]L. B. Leder and J. Arol Simpson, Rev. Sci. Instr. 29, 571 (1958).
[8]E. M. Purcell, Astrophys. J. 116, 457 (1952).
[9]W. L. Fite, R. F. Stebbings, and R. T. Brackmann, Phys. Rev. 116, 356 (1959).

BARYON-EXCHANGE MODEL IN ISOBAR PRODUCTION*

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Baryon exchange has been considered in low-energy pion-nucleon elastic scattering with considerable success.[1] The purpose of this note is to extend the idea to inelastic isobar production processes and to present some experimental evidence for the mechanism.

Consider the general reaction

$$M_i + B_i \to M_f + B_f,$$

where M_i, M_f, B_i, and B_f are initial meson, final meson, initial baryon, and final baryon, respectively. The baryon-exchange graph is shown in Fig. 1(a). The two incident particles, M_i and B_i, with four-momenta k_i and p_i, collide by exchanging a single virtual baryon B with four-momentum Δ. The final-state particles, M_f and B_f, emerge with four-momenta k_f and p_f. The rest masses of M_i, M_f, B_i, and B_f are w, w', W, and W', respectively. In the metric used,

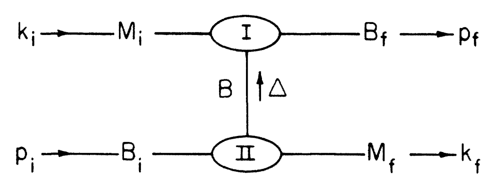
$$k_i^2 = -w^2.$$

The squared four-momentum of the exchanged baryon is given by

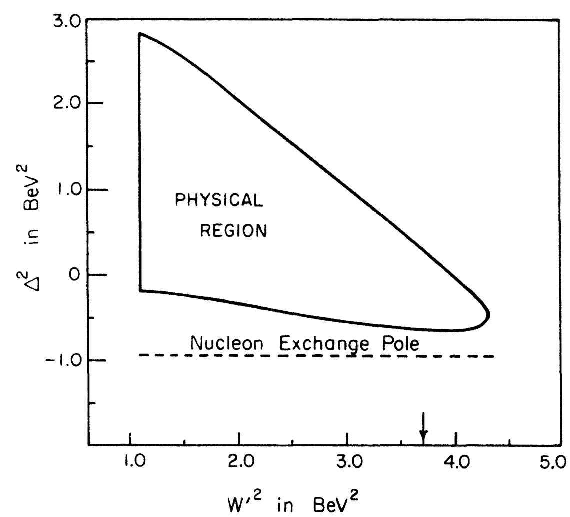
$$\Delta^2 = (p_f - k_i)^2 = (p_i - k_f)^2.$$

Whether Δ^2 is spacelike (positive) or timelike (negative) depends on the relative masses of the particles involved.[2] If baryon exchange is to become important it should appear when Δ^2 is a minimum (as timelike as possible), so that the physical region approaches the pole $\Delta^2 = -m_B^2$, where m_B is the rest mass of the exchanged baryon.

Consider the case where $W' > w$, $W > w'$, and B_f is an isobar which decays strongly into two particles. A Chew-Low diagram[3] of the squared effective mass of the decay paticles, W'^2, versus Δ^2 will then be of the form shown in Fig. 1(b). Note that in this case Δ^2 can be timelike. The



(a)



(b)

FIG. 1. (a) Baryon exchange diagram for the reaction $M_i + B_i \to M_f + B_f$. k_i, p_i, k_f, and p_f are the four-momenta of initial meson M_i, initial baryon B_i, final meson M_f, and final baryon B_f, respectively. B is the intermediate baryon with four-momentum Δ. (b) Chew-Low diagram for the reaction $\pi + p \to \pi + \pi + N$ for 2.16-BeV/c incident pions. W' is the effective mass of the final-state nucleon and one of the final pions. Δ is the four-momentum transfer between the initial nucleon and the remaining final pion. The arrow indicates the position of the $\Delta(1920)$ isobar.

dashed line represents the nucleon-exchange pole. One might expect nucleon exchange to become important when the effective mass at which Δ^2 becomes a minimum is in the vicinity of an isobar.

It can be shown that the minimum value of Δ^2 is given by

$$\Delta_{\min}^2 = -(W - w')^2.$$

The effective mass at which this minimum value of Δ^2 occurs is given by

$$W'^2 = (W - w')(W - w' + 2E_w) + w^2, \quad (1)$$

where E_w is the total energy of M_i, the incident meson, in the rest frame of B_i. For appropriate values of E_w, W' will correspond to particular isobars.

A study was made of the reactions

$$\pi^- + p \to \pi^- + \pi^0 + p, \quad (2)$$

$$\pi^- + p \to \pi^- + \pi^+ + n \quad (3)$$

for 2.16-BeV/c incident pions in the Alverez 72-in. bubble chamber. The reactions were determined by the usual χ^2 criteria ($\chi^2 < 6.0$) and ionization estimates of the positive track using the FOG-CLOUDY-FAIR programs. Only unambiguous events were used in the analysis.

The dominant process for the reactions studied was the expected rho-meson production, as was seen from a di-pion effective-mass distribution The diagram of Fig. 1(b), however, suggests that one might expect to see the effect of nucleon exchange in the production of the $\Delta(1920)$ isobar. The pi-nucleon effective-mass distributions (Fig. 2) show a significant number of events above phase space at the $\Delta(1920)$ mass for only those charged states that are consistent with nucleon exchange. Furthermore, the $\Delta(1920)$ isobar is produced predominantly in the forward hemisphere, in the barycentric system, relative to the initial pion, as seen in Fig. 3(a). The theoretical curve was obtained assuming the angular dependence of the cross section comes only from the nucleon propagator squared times a phase-space factor. A detailed calculation would, of course, be useful for the interpretation of the experimental results. For comparison, the preferred backward production of the $\Delta(1238)$, shown in Fig. 3(b), is what one would expect for a rho-exchange process, which is also suggested by the observed charged states in Fig. 2. Finally, a Treiman-Yang angle between the plane formed by particles of vertex I and the plane formed by particles of vertex II of Fig. 1 is defined in the rest frame of B_f [the $\Delta(1920)$ isobar]. The observed correlation between these planes, which we attribute to the spin of the nucleon, is shown in Fig. 4. There would be no reason to expect a correlation between these particular planes unless the diagram in Fig. 1(a) were important.

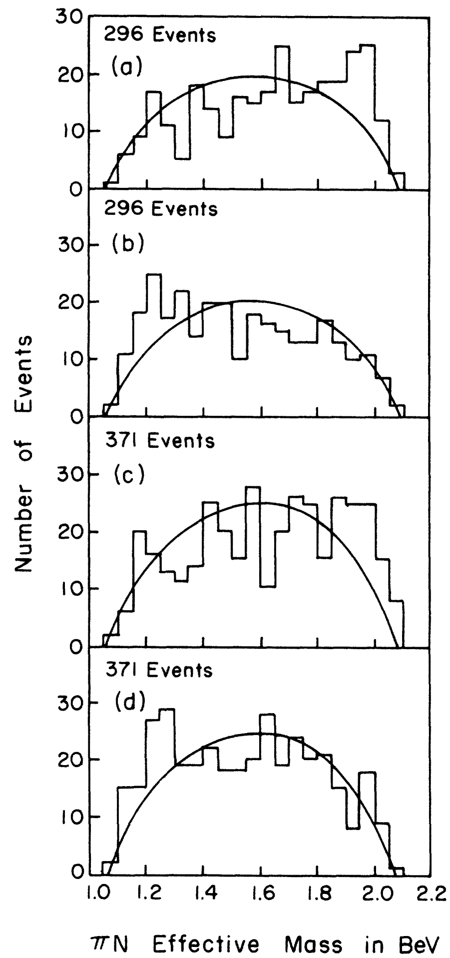


FIG. 2. Pi-nucleon effective-mass distributions. (a) is the π^-p mass distribution for Reaction (2). (b) is the π^0p distribution for (2). (c) is π^-n distribution for (3). (d) is the π^+n distribution for (3). The smooth curve is phase-space normalized to total number of events.

$\Delta(1920)$ isobar production, and therefore nucleon exchange, may account for the observed increase in the total π^-p cross section with 2.08-BeV/c incident pions.[4] The isobar-production cross section was found to be approximately 1 mb. Consideration of other decay modes will, of course, give a larger value.

The results of the Berkeley group[5] provide corroborating evidence for this model. They have made an extensive study of Reaction (3) with in-

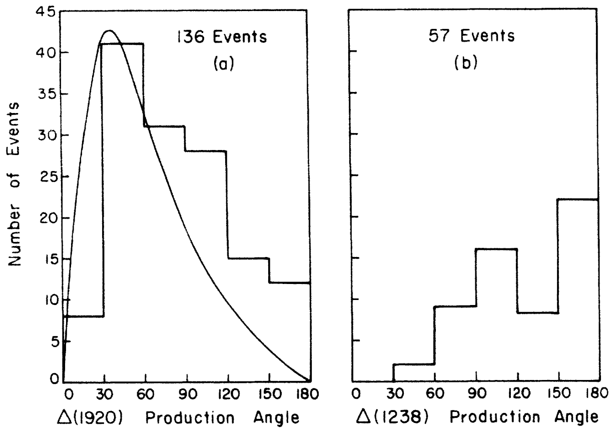


FIG. 3. Distribution of isobar production angles relative to initial pion in the barycentric system. In (a) data are plotted for those events where $1.85 < M_{\pi^- p}$ and $M_{\pi^- n} < 2.05$ BeV. In (b) data are plotted for those events where $1.20 < M_{\pi^- p}$, $M_{\pi^0 p}$, and $M_{\pi^+ n} < 1.25$ BeV. In both (a) and (b), rho events ($0.7 < M_{\pi\pi} < 0.8$ BeV and squared four-momentum transfer to nucleon less than 0.25 BeV^2) are excluded.

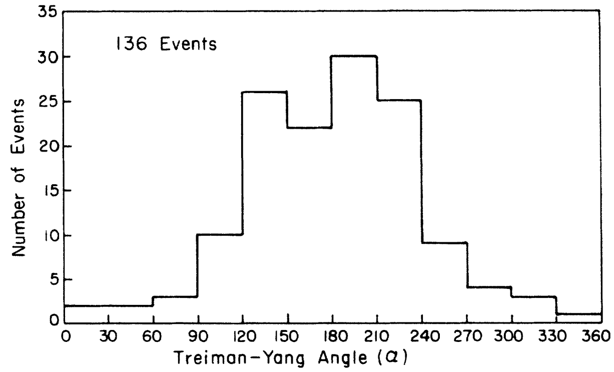


FIG. 4. α is defined in the rest frame of the $\Delta(1920)$ isobar as

$$\cos\alpha = \frac{\vec{k}' \times \vec{k}_i}{|\vec{k}' \times \vec{k}_i|} \cdot \frac{\vec{k}_f \times \vec{p}_i}{|\vec{k}_f \times \vec{p}_i|},$$

where $\vec{k}'$, $\vec{k}_i$, $\vec{k}_f$, and $\vec{p}_i$ are the three-momenta of the isobar decay pion, the initial pion, the remaining pion, and the incident proton, respectively. The events plotted here are the same as those plotted in Fig. 3(a).

cident beam energies between 360 and 780 MeV. An examination of Eq. (1) reveals that at these energies the $\Delta(1238)$ isobar should be produced via nucleon exchange. They find the negative $\Delta(1238)$ isobar but not the positive one. Furthermore, at the higher energies they find the isobar produced predominantly in the forward hemisphere.

On the other hand, Guiragossián[6] has studied Reactions (2) and (3) at 3.3 BeV/c. He found no evidence for any of the negatively charged isobars. A study of Eq. (1) shows that at this energy there are no known isobars with a mass appropriate to the nucleon-exchange process.

Further evidence for the model comes from the reactions

$$K^- + p \to \Sigma^-(1385) + \pi^+, \qquad (4)$$

$$K^- + p \to \Sigma^+(1385) + \pi^-. \qquad (5)$$

The final observable state in both cases is $\Lambda(1115) + \pi^+ + \pi^-$. At 2.2-BeV/$c$ incident beam momentum, the relative production rate, R, of (4) to (5) is approximately zero[7] and the decay of $\Sigma^+(1385)$ relative to the production plane is consistent with a vector-meson exchange process.[8] As one goes to lower energies, R increases[9] until at 1.15-BeV/c incident kaons, $R = 1.45$.[10] Furthermore, at lower energies the decay of $\Sigma^+(1385)$ is no longer consistent with a vector-meson exchange. A study of Eq. (1) for this case shows that at the lower energies one expects nucleon exchange to be more important in the production of $\Sigma^-(1385)$. The effect of the mechanism is therefore seen in the increased production of the negative isobar and in the interference of Reaction (4) with Reaction (5).

Kehoe[11] has studied the reaction

$$K^+ + p \to \Delta^{++}(1238) + K^0$$

at 910 MeV/c. The results are in excellent agreement with a vector-meson exchange process. This is in contrast to the K^- interactions at lower energies where interference from nucleon exchange appears to become important. Kehoe's results are consistent with the nucleon-exchange model. Since isobars with positive strangeness do not exist, one would not expect an enhancement of the nucleon-exchange graph which could interfere with $\Delta(1238)$ isobar production.

As has previously been pointed out, baryon exchange has been successful in low-energy pion-nucleon interactions.[1] The effect is reflected in the predominant backward scattering in

$$\pi^+ + p \to \pi^+ + p,$$

and

$$\pi^- + p \to \pi^0 + n,$$

but preferred forward scattering in

$$\pi^- + p \to \pi^- + p$$

at low energies.[12] A study of Eq. (1) shows that W', the mass of the final-state baryon, is equal to the nucleon mass for zero-energy incident pions. Nucleon exchange at low energies, therefore, appears as a special case of a more general scheme.

The proposed model, therefore, appears to be consistent with a number of other experiments which have been examined, as well as with our results for production of the Δ(1920) isobar. It would seem worth while to look for its effects in other reactions. Furthermore, it should be useful to consider the interference effects of possible baryon-exchange poles in experiments designed to isolate vector-meson exchange mechanisms.

We would like to thank the Alvarez group, and in particular Dr. Gerald Smith, for providing us with the film and for their helpful cooperation in the experimental study of the problem. We are indebted to Dr. Howard White and his group for providing us with the FOG-CLOUDY-FAIR programs and for their continuous efforts in solving programming problems. We also wish to thank Mr. Ward Schultz for his help in measuring procedure and processing the data. Finally, we wish to acknowledge many helpful and stimulating discussions with Mr. William B. Campbell.

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[1]Geoffrey F. Chew, S-Matrix Theory of Strong Interactions (W. A. Benjamin, Inc., New York, 1962), p. 81. References to original papers are also given.

[2]F. Salzman and G. Salzman, Phys. Rev. 125, 1703 (1960).

[3]G. F. Chew and F. E. Low, Phys. Rev. 113, 1640 (1959).

[4]See, for example, A. N. Diddens, E. W. Jenkins, T. F. Kycia, and K. F. Riley, Phys. Rev. Letters 10, 262 (1963).

[5]J. Kirz, J. Schwartz, and R. D. Tripp, Phys. Rev. 130, 2481 (1963).

[6]Zaven G. T. Guiragossián, Phys. Rev. Letters 11, 85 (1963).

[7]L. Bertanza, V. Brisson, P. L. Connolly, E. L. Hart, I. S. Mittra, G. C. Moneti, R. R. Rau, N. P. Samios, I. O. Skillicorn, S. S. Yamamoto, M. Goldberg, J. Leitner, S. Lichtman, and J. Westgard, Phys. Rev. Letters 10, 176 (1963).

[8]L. Stoldolsky and J. J. Sakurai, Phys. Rev. Letters 11, 90 (1963).

[9]J. Button-Shafer, D. Huwe, and J. J. Murray, Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 303.

[10]R. H. Dalitz, Strange Particles and Strong Interactions (Oxford University Press, New York, 1962), p. 97.

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

[12]H. L. Anderson, E. Fermi, R. Martin, and D. E. Nagle, Phys. Rev. 91, 155 (1953).

POSSIBLE RESONANCE AT 829 MeV IN ΛK^0 PRODUCTION

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Some time ago Bertanza et al.[1] observed an anomalous behavior of the polarization of the Λ particles in the reaction $\pi^- + p \to \Lambda + K^0$ at an incident pion kinetic energy of 829 MeV. From a polynomial analysis they found that this feature was related to the presence of partial waves higher than P, and since this effect died very fast both below and above this energy the authors suggested that the explanation could be the existence of a ΛK resonance (Z_1^*) at about a center-of-mass energy of 1650 MeV. It is the purpose of this Letter to present some rather strong evidence to the fact that there is indeed such a resonance and that its spin-parity assignment should be $\frac{5}{2}^+$. It is then natural to try to identify it with the $F_{5/2}$ resonance in pion-nucleon scattering, which has been assumed up to now to be located at 1688 MeV,[2] and we speculate on this possibility. If this turns out to be correct, our estimated value for the contribution of the $F_{5/2}$ resonance to the ΛK^0 production cross section is in agreement with the prediction of Carruthers's model for the higher meson-baryon resonances based on SU(3),[3] if we assume for the radius of interaction the value estimated by Glashow and Rosenfeld.[4]

A while ago we proposed a model for low-energy ΛK^0 production[5] which gave either excellent or reasonably good fits to the angular distributions, polarizations, and cross sections up to a center-of-mass energy of about 1700 MeV except at the energy of the Bertanza et al. anomaly. In this model it was assumed that the K^* exchange term