# Spin and Parity of the Ξ* (1530 MeV)†

JANICE BUTTON-SHAFER, JAMES S. LINDSEY, JOSEPH J. MURRAY, AND GERALD A. SMITH
*Lawrence Radiation Laboratory, University of California, Berkeley, California*
(Received 12 August 1965)

Results are presented from the spin-parity analysis of reactions of the type $K^-+p\rightarrow \Xi K\pi\pi$ in which nearly pure samples of the $\Xi^*(1530)$ are produced. Comparison is made with the analysis of randomly generated events. The hypothesis of $P_{3/2}$ fits the data better than that of $D_{3/2}$, the latter having a confidence level of $\leqslant 0.03$. Spin $\frac{5}{2}$ is not required.

THE $\Xi^*(1530)$ was shown by Schlein *et al.* to have spin $\geqslant\frac{3}{2}$.[1] However, its parity was not established by these authors; they concluded that $P_{3/2}$ (or $D_{5/2}$) was the preferred assignment for the $\Xi^*$ on the basis of a confidence level of 0.035 for the $D_{3/2}$ hypothesis. Connolly *et al.* also observed the $\Xi^*(1530)$ and found some indication for spin $>\frac{1}{2}$.[2] Our report supports the spin $\geqslant\frac{3}{2}$ assignment and presents further evidence for the $\Xi^*-\Xi$ relative parity that requires a $P_{3/2}$ (or $D_{5/2}$) assignment for the $\Xi^*$.

The $\Xi$-$\pi$ resonance at 1530 MeV ($T=\frac{1}{2}$) has been analyzed in the following reactions:

$$\begin{array}{llll}(A) & K^-+p\rightarrow \Xi^-K^+\pi^0 & (B) & K^-+p\rightarrow \Xi^-K^+\pi^+\pi^- \\ & \rightarrow \Xi^-K^0\pi^+ & & \rightarrow \Xi^-K^0\pi^+\pi^0 \\ & \rightarrow \Xi^0K^+\pi^-, & & \rightarrow \Xi^0K^0\pi^+\pi^-.\end{array} \quad (1)$$

These interactions were produced with beams of $K^-$ mesons, at momenta of 2.45, 2.55, 2.6, and 2.7 GeV/$c$, incident on the 72-in. hydrogen bubble chamber at the Bevatron. The $\Xi K\pi$ sample of $\approx 900$ events contained about 200 $\Xi^*$'s; the $\Xi K\pi\pi$ sample of $\approx 150$ events included about 100 $\Xi^*$'s.

The three-body events (A) suffered from interference of the $K^*$ resonance with the $\Xi^*$ band, whereas the four-body events (B) were relatively free from $K^*$-$\Xi^*$ interference.[3] (In the former class of events, the pion can form $T=\frac{1}{2}$ resonances simultaneously with the $\Xi$ and the $K$; however, in the latter class, neither of the two pions can be shared by $\Xi^*$ and $K^*$ in two of the three reactions.)

The width of the $\Xi^*$ in our data is about 20 MeV, even with interfering $K^*$ events eliminated. (Most of this width is measurement error, as the true width is known to be about 7 MeV.[1]) Thus all $\Xi$-$\pi(T=\frac{1}{2})$ combinations with an effective mass falling within the interval 1510 to 1555 MeV were considered $\Xi^*$ candidates.[4] The background in this interval under the $\Xi^*$ peak is fairly appreciable for the three-body sample (Fig. 2 of Ref. 5) but it is almost negligible for the "clean" four-body events (no $K^*$ interference), as shown in Fig. 1. (See also Ref. 6.)

Because of the interference and background from which the $\Xi^*K$ events suffered, the emphasis in our analysis is on the $\Xi^*K\pi$ class of events.

The $\Xi^*(1530)$ decay was analyzed through use of the method proposed by Byers and Fenster[7]; this technique was applied in the first study of the $\Xi^*(1530)$[1] and was also used for an extension of the $Y_1^*(1385)$ spin-parity analysis.[8] Moments of the $\Xi^*$ decay distributions were found: $\langle Y_{LM}\rangle$ with even $L$ from the $\Xi$ angular distribution, $\langle P_{\parallel}Y_{LM}\rangle$ with odd $L$ from the $\Xi$ longitudinal-polarization distribution, and $\langle P_{\perp}\mathfrak{D}_{M1}{}^{L}\rangle$ with odd $L$

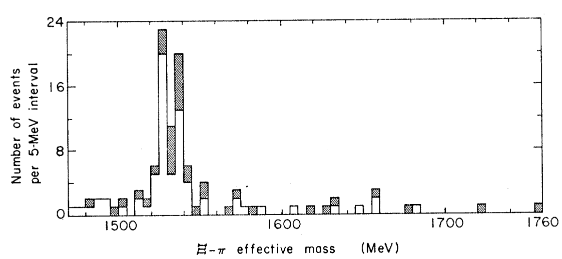


FIG. 1. Histogram of $\Xi$-$\pi$ effective mass from the "clean" reactions, $K^-+p\rightarrow\Xi^-K^+\pi^+\pi^-$ and $K^-+p\rightarrow\Xi^0K^0\pi^+\pi^-$. The $\Xi^0$ events are shaded.

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] P. E. Schlein, D. D. Carmony, G. M. Pjerrou, W. E. Slater, D. H. Stork, and H. K. Ticho, Phys. Rev. Letters **11**, 167 (1963). The parity $\chi^2$ values of Schlein *et al.* indicate confidence levels of 0.035 for the $D_{3/2}$ hypothesis and one of 0.83 for the $P_{3/2}$ assumption.

[2] P. L. Connolly, E. L. Hart, G. Kalbfleisch, K. W. Lai, G. London, G. C. Moneti, R. R. Rau, N. P. Samios, I. O. Skillicorn, S. S. Yamamoto, M. Goldberg, M. Gundzik, J. Leitner, and S. Lichtman, *Proceedings of the Sienna International Conference on Elementary Particles, September 1963*, (Società Italiana di Fisica, Bologna, Italy, 1963), Vol. I, p. 125. The $\Xi^*$ study described here was made difficult by the presence of the $K^*(880)$ and an apparent $\kappa(730)$.

[3] In a small number of four-body events, the $\Xi^*(1530)$ was a strong-decay product of a primary resonance, the $\Xi^*(1820)$. (See Ref. 3.) For these events, the angular distribution of $\Xi^*(1820)$ decay was ignored (i.e., averaged over) for the study of the $\Xi^*(1530)$ decay. (See Ref. 9.)

[4] The UCLA group defined as $\Xi^*$ any $\Xi$-$\pi$ combination with mass from 1515 to 1545 MeV.[1] Because of our larger observed width, we have defined as $\Xi^*$ the somewhat larger mass range of 1510 to 1555 MeV. In the $\Xi^*K\pi$ "clean" sample of events, the width of the $\Xi^*(1530)$ was 15 to 20 MeV; our estimate of the width of the resolution function is perhaps $7\pm3$ MeV, after correction for underestimation of fitting errors. This is compatible with the UCLA observation.

[5] G. A. Smith, J. S. Lindsey, J. Button-Shafer, and J. J. Murray, Phys. Rev. Letters **14**, 25 (1965).

[6] G. A. Smith, J. S. Lindsey, J. J. Murray, J. Button-Shafer, A. Barbaro-Galtieri, O. I. Dahl, P. Eberhard, W. E. Humphrey, G. R. Kalbfleisch, R. R. Ross, F. T. Shively, and R. D. Tripp, Phys. Rev. Letters **13**, 61 (1964).

[7] N. Byers and S. Fenster, Phys. Rev. Letters **11**, 52 (1963).

[8] J. Button-Shafer and D. O. Huwe, Phys. Rev. **134**, B1372 (1964).

TABLE I. Evaluations of $t_{LM}$ parameters.

| $J$ | $L$ | $M$[a] | $t_{LM}$(from $I$)[b] | $t_{LM}$(from $IP_{\parallel}$) | $\gamma t_{LM}$(from $IP_{\perp}$) |
|---|---|---|---|---|---|
| A. For 48 forward-produced $\Xi^*$'s. | | | | | |
| all | 0 | 0 | 1.000 | | |
| $\frac{1}{2}$ | 1 | 0 | | $0.21\pm0.58$ | $-0.43\pm0.35$ |
| $\frac{3}{2}$ | 1 | 0 | | $0.47\pm1.30$ | $-0.49\pm0.39$ |
| | 2 | 2 | $0.05\pm0.09+i(0.00\pm0.11)$ | | |
| | 2 | 0 | $-0.09\pm0.16$ | | |
| | 3 | 2 | | $0.03\pm0.28+i(0.03\pm0.31)$ | $-0.66\pm0.25+i(0.01\pm0.23)$ |
| | 3 | 0 | | $-0.01\pm0.54$ | $0.29\pm0.30$ |
| $\frac{5}{2}$ | 1 | 0 | | $0.71\pm1.98$ | $-0.49\pm0.40$ |
| | 2 | 2 | $0.04\pm0.08+i(0.00\pm0.10)$ | | |
| | 2 | 0 | $-0.08\pm0.15$ | | |
| | 3 | 2 | | $0.05\pm0.51+i(0.06\pm0.58)$ | $-0.81\pm0.30+i(0.01\pm0.28)$ |
| | 3 | 0 | | $-0.02\pm1.00$ | $0.36\pm0.37$ |
| | 4 | 4 | $-0.17\pm0.10+i(0.08\pm0.11)$ | | |
| | 4 | 2 | $-0.13\pm0.08+i(-0.13\pm0.11)$ | | |
| | 4 | 0 | $0.26\pm0.19$ | | |
| | 5 | 4 | | $-0.02\pm0.27+i(0.61\pm0.28)$ | $-0.07\pm0.23+i(-0.07\pm0.24)$ |
| | 5 | 2 | | $0.06\pm0.23+i(0.39\pm0.21)$ | $0.26\pm0.23+i(0.27\pm0.24)$ |
| | 5 | 0 | | $0.14\pm0.41$ | $-0.11\pm0.39$ |
| B. For 29 backward-produced $\Xi^*$'s. | | | | | |
| all | 0 | 0 | 1.000 | | |
| $\frac{1}{2}$ | 1 | 0 | | $0.00\pm0.69$ | $-0.29\pm0.53$ |
| $\frac{3}{2}$ | 1 | 0 | | $0.01\pm1.55$ | $-0.33\pm0.59$ |
| | 2 | 2 | $-0.01\pm0.16+i(-0.17\pm0.12)$ | | |
| | 2 | 0 | $0.27\pm0.15$ | | |
| | 3 | 2 | | $0.07\pm0.43+i(0.30\pm0.41)$ | $0.31\pm0.36+i(0.15\pm0.28)$ |
| | 3 | 0 | | $1.15\pm0.54$ | $0.75\pm0.38$ |
| $\frac{5}{2}$ | 1 | 0 | | $0.01\pm2.37$ | $-0.33\pm0.60$ |
| | 2 | 2 | $-0.01\pm0.15+i(-0.16\pm0.11)$ | | |
| | 2 | 0 | $0.26\pm0.14$ | | |
| | 3 | 2 | | $0.13\pm0.78+i(0.56\pm0.75)$ | $0.38\pm0.44+i(0.19\pm0.35)$ |
| | 3 | 0 | | $2.11\pm1.00$ | $0.92\pm0.46$ |
| | 4 | 4 | $0.26\pm0.12+i(0.24\pm0.17)$ | | |
| | 4 | 2 | $0.03\pm0.12+i(0.19\pm0.14)$ | | |
| | 4 | 0 | $-0.08\pm0.18$ | | |
| | 5 | 4 | | $0.71\pm0.31+i(0.18\pm0.43)$ | $0.49\pm0.28+i(0.21\pm0.33)$ |
| | 5 | 2 | | $-0.08\pm0.35+i(-0.25\pm0.32)$ | $-0.42\pm0.28+i(-0.10\pm0.27)$ |
| | 5 | 0 | | $0.95\pm0.48$ | $0.36\pm0.42$ |

[a] Only positive $M$ values are given because $t_{L,-M}=(-)^M t_{LM}^*$.
[b] $I$ refers to $I(\theta,\phi)$, the decay angular distribution; $P_{\parallel}$ and $P_{\perp}$ refer to polarization components, also functions of $\theta$ and $\phi$.

from the $\Xi$ transverse-polarization distribution. The complexity of the moments—i.e., the highest $L$ value giving a nonzero moment—indicated the highest spin assignment required. Comparison of each moment of the $\Xi$ transverse polarization with the corresponding moment of its longitudinal polarization gave the parity of the decay. (See Refs. 1, 7, and 8 for further details.)

The $\Xi^*$ decay was investigated with and without restrictions on the production angle of the $\Xi^*$, the restrictions resulting in the selection of samples of high-polarization $\Xi^*$'s. The coordinate system used for analysis had as its axes the normal to the $\Xi^*$ production plane ($z$), the incident-beam direction ($y$), and an orthogonal direction in the production plane ($x$).[9] The value of $\alpha_{\Xi}$ utilized was $-0.43$, an approximate best value from early $\Xi$ studies at Berkeley; the $\Xi$ spin was taken to be $\frac{1}{2}$.[10] (The uncertainty in $\alpha_{\Xi}$ was insignificant in comparison with the statistical errors in moment determinations.)

The backward-produced $\Xi^*$'s showed a higher polarization than did the forward-produced $\Xi^*$'s of the $\Xi^*K\pi$ events. With all three four-body reactions of Eq. (1) combined, the numbers of forward and backward $\Xi^*$'s were 56 and 47, respectively. With the use of only the two reactions without $K^*$-$\Xi^*$ interference, these numbers became 48 forward and 29 backward.

[9] The definition of the normal ($\hat{K}_{\text{inc}}\times\hat{\Xi}^*$) was the same for $\Xi^*K\pi$ as for $\Xi^*K$ events. The Byers-Fenster analysis should not be affected by the noncoplanarity of the "three-particle" ($\Xi^*K\pi$) final state. The theory assumes merely that there exists a collection of "particles," describable in their rest frame by a set of spin-state parameters; footnote 7 of the Byers and Fenster article[7] states that "components of the vectors and tensors refer to any right-handed set of Cartesian coordinate axes chosen without reference to the $Y^*$ decay." The amount of $\Xi^*(1820)$ in the "clean" sample of $\Xi^*K\pi$ final states (that used for analysis) was very small ($\approx 6\pm5\%$). Even for these, the arguments just given appear to justify the customary application of the Byers-Fenster theory without regard to the $\Xi^*(1820)$. With the $z$ axis as defined, odd-$M$ moments vanish (checkerboard theorem) provided final $K$ and $\pi$ directions are ignored.

[10] Spin $\frac{1}{2}$ for the $\Xi$ is supported by analyses at UCLA [D. D. Carmony, G. M. Pjerrou, P. E. Schlein, W. E. Slater, D. H. Stork, and H. K. Ticho, Phys. Rev. Letters **12**, 482 (1964)], and at Berkeley [J. P. Berge, P. E. Eberhard, J. R. Hubbard, G. R. Kalbfleisch, J. Button-Shafer, F. T. Solmitz, M. L. Stevenson, S. G. Wojcicki, and P. G. Wohlmut (unpublished)]. With the conclusion of the Berkeley work just cited, the approximate world-average value of $\alpha_{\Xi}$ is $-0.40\pm0.05$.

TABLE II. Spin and parity results.

| Sample | No. of events | Spin[a] $\chi^2(\frac{1}{2})$ | $\chi^2(\frac{3}{2})$ | Parity[a] $\chi^2(P_{3/2})$ | $\chi^2(D_{3/2})$ |
|---|---|---|---|---|---|
| Forward Ξ*'s | 48 | 48 | 22 | 4.2 | 3.2 |
| | | [<0.005][b] | [0.10] | [0.37] | [0.52] |
| Backward Ξ*'s | 29 | 401 | 55 | 0.78 | 18.3 |
| | | [$<10^{-4}$] | [$<10^{-4}$] | [0.94] | [0.001] |
| Sum of $\chi^2$ values: | | 449 | 77 | 5.0 | 21.5 |
| | | [$<10^{-4}$] | [$<10^{-4}$] | [0.75] | [0.005] |
| UCLA Ξ*'s[c] | 80 | 47 | 18 | 1.5 | 10.3 |
| | | [0.003] | [0.27] | [0.83] | [0.035] |

[a] The number of degrees of freedom for each $\chi^2$ is as follows: 24 for $\chi^2(\frac{1}{2})$, 15 for $\chi^2(\frac{3}{2})$, and 4 for each parity $\chi^2$.
[b] The number in brackets is the confidence level for the $\chi^2$ value given above. It is underestimated (especially for the spin $\chi^2$ values) because of the smallness of samples. (See Figs. 3 and 4).
[c] See Ref. 1.

These samples of data were analyzed to determine the moments of their decay distributions.

It is convenient to characterize each $L$, $M$ moment of a decay distribution by a complex $t_{LM}$ parameter to which it is related by a multiplicative constant (essentially a Clebsch-Gordan coefficient). These $t_{LM}$'s represent the spin-operator expectation values that describe the initial Ξ* spin state. Evaluations of the $t_{LM}$ parameters for the clean samples described above are presented in Table I.

Each $\gamma t_{LM}$ derives from an odd-$L$ transverse polarization moment $\langle P_\perp \mathfrak{D}_{M1}{}^L\rangle$; the corresponding $t_{LM}$ derives from a longitudinal polarization moment $\langle P_\parallel Y_{LM}\rangle$. On the average, the corresponding $\gamma t_{LM}$ and $t_{LM}$ must agree in magnitude and have a relative sign determined by the parity of the Ξ* decay. (For decay with $l=J-\frac{1}{2}$, the parameter $\gamma=+1$; whereas for $l=J+\frac{1}{2}$, $\gamma=-1$.) Thus the relative sign of corresponding entries in the last two columns of Table I provides parity information.

We used some of the moments projected from the experimental decay distributions to calculate smooth curves that are compared with histograms representing these distributions in Fig. 2 (for one of the data samples). Only the dependence on the polar angle $\theta$ is shown. In the distribution of the transverse polarization, the curve most closely matching the histogram is not shown; instead the curve predicted from the moments of the longitudinal polarization is displayed. (The amplitude of this curve has a fractional uncertainty of almost 50%.) Different spin and parity assumptions require different curves, as each moment of $IP_\perp$ is proportional to $\gamma(2J+1)$ times the corresponding moment of $IP_\parallel$. [Here $IP$ represents the Ξ*-decay angular distribution $I(\theta)$ times a polarization component $P(\theta)$ of the Ξ.] The azimuthal dependences (demanded by nonzero Re$t_{22}$, Im$t_{22}$, Re$t_{32}$, or Im$t_{32}$) are not shown for the angular or polarization distributions; also, the statistical correlations of errors cannot be shown. Thus the estimate of the probability of any hypothesis cannot be made properly by a simple comparison of the curves and data of Fig. 1. Nevertheless, the curves indicate somewhat better agreement with the $P_{3/2}$ than with the $D_{3/2}$ hypothesis.

Calculations were made of both a spin $\chi^2$ and a parity $\chi^2$ for each of several assumptions. These $\chi^2$ quantities were evaluated as follows:

$$\chi_J{}^2=\sum_{L>2J}^{5}\sum_{M} t_{LM}G_{LM,L'M'}{}^{-1}\,t_{L'M'}\,,$$

$$\chi_P{}^2=\sum_{\text{odd }L=1}^{2J}\sum_{M}(t_{LM}{}^{\parallel}-t_{LM}{}^{\perp})\times H_{LM,L'M'}{}^{-1}(t_{L'M'}{}^{\parallel}-t_{L'M'}{}^{\perp})\,,$$

with $G$ and $H$ representing the appropriate error matrices, and with $t^\parallel$ and $t^\perp$ obtained from moments of longitudinal and transverse polarization components, respectively. Table II presents the $\chi^2$'s and (sometimes misleading) confidence levels for the various hypotheses, as applied to the two $\Xi^*K\pi$ samples of data. The values obtained by Schlein *et al.* (UCLA) are also shown for comparison.

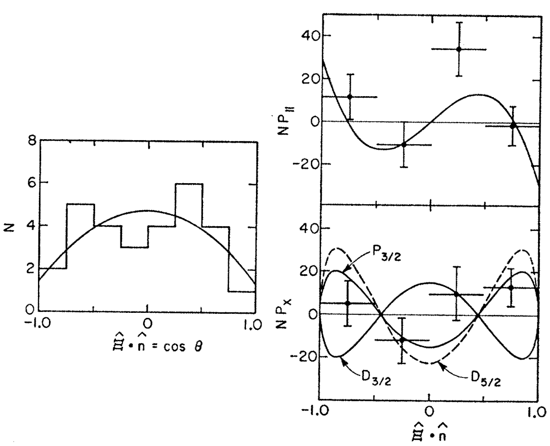


FIG. 2. Decay distributions for backward Ξ*'s. The angular distribution of decay, the longitudinal-polarization distribution of the Ξ, and the distribution of one component of transverse polarization of the Ξ are shown as functions of the polar angle $\theta$ only. [The symbol $N$ represents the number of events per $\cos\theta$ interval. The $P_x$ polarization is $\mathbf{P}\cdot\hat{\Xi}\times(\hat{\Xi}\times\hat{n})/|\hat{\Xi}\times(\hat{\Xi}\times\hat{n})|$.] The curves were obtained from program-calculated moments. Those of the $NP_x$ plot were predicted for various spin-parity assumptions on the basis of $NP_\parallel$ moments.

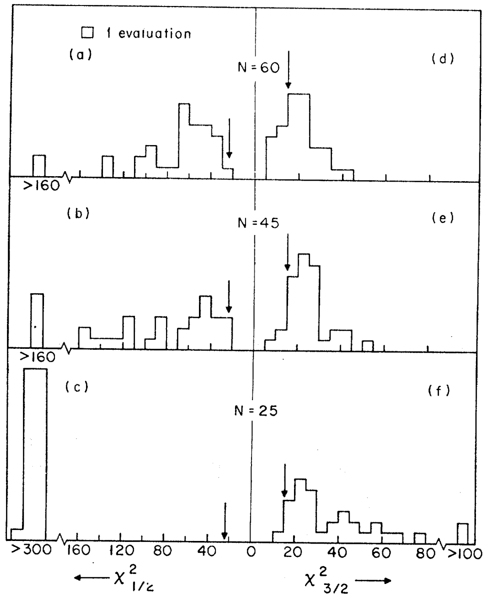


FIG. 3. Histograms of spin $\chi^2$ evaluations for samples of varying sizes ($N$ "events") generated randomly. The correct spin is $\frac{3}{2}$. The $\chi^2$ evaluations are so plotted that $\chi^2(\frac{3}{2})$ increases to the right and $\chi^2(\frac{1}{2})$ increases to the left. The arrows indicate the expected average $\chi^2$ for samples having the spin indicated by the subscript of the $\chi^2$ plotted.

Approximately 100 samples of "events" were randomly generated by a computer program in accordance with distributions characterized by moments similar to those of the actual experimental data. In order for the behavior of the $\chi^2$ quantities to be determined as the number of events per sample became small, the sample sizes were varied (60, 45, and 25 events per sample). Analysis of these computer-generated samples of "events" with the same program (SPINPAR) used for analysis of the real data yielded moment evaluations (centering about the input values) and $\chi^2$ values. With diminishing sample size, the mean value of the spin $\chi^2$ became larger than that expected for normally distributed variables. Figure 3 shows this behavior. Also, parity $\chi^2$ values tended to become larger as the size of the sample decreased. Figure 4 is a scatter plot in parity $\chi^2$ values (for $J=\frac{3}{2}$), with each point giving the values of the $D_{3/2}$ and $P_{3/2}$ $\chi^2$'s for one computer-generated sample; the "input" was that of the $D_{3/2}$ state for ease of testing the experimental data for that hypothesis. (The assumption of $P_{3/2}$ for computer input would cause the distribution to be reflected about the 45-deg line of the plot.) Even for the 25-event samples, the points clearly tend to fall below the 45-deg equal-confidence line.

As the final parity conclusions (Table II) drawn from the experimental data are based on the addition of $\chi^2$ values for two samples of 29 events and 48 events (the backward- and forward-produced $\Xi^*$'s), the parity $\chi^2$ values of the randomly generated samples of 25 events and of 45 events have been added. (The pairing of samples was random.) The resulting $\chi^2$ values for these combined samples of 70 events are shown in Fig. 5.

We analyzed separately the experimental data with a $\Xi^*$ mass above 1530 MeV and those with a $\Xi^*$ mass below 1530 MeV. Results on these "high-mass" and "low-mass" samples of events were quite similar. We also investigated distribution moments expected to be zero (the odd-$L$ moments of the angular distribution

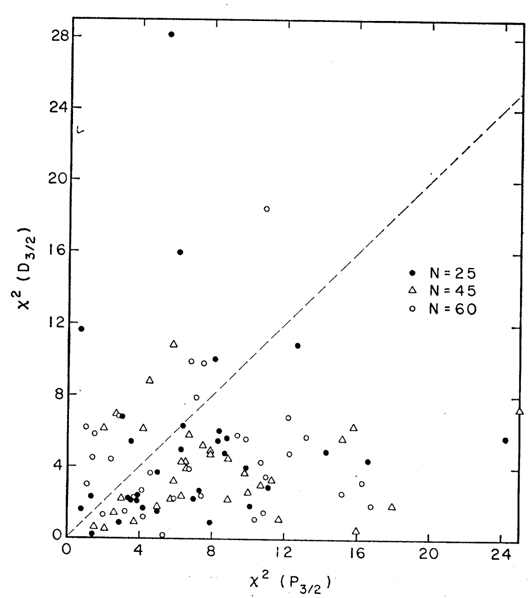


FIG. 4. A scatter plot of parity $\chi^2$ values (with $J=\frac{3}{2}$): $\chi^2$ for the $D_{3/2}$ hypothesis versus that for the $P_{3/2}$ hypothesis. The samples are randomly generated events, with $D_{3/2}$ the correct assignment. The sizes of the samples are indicated in the legend. (The experimental evaluations are given in Table II.)

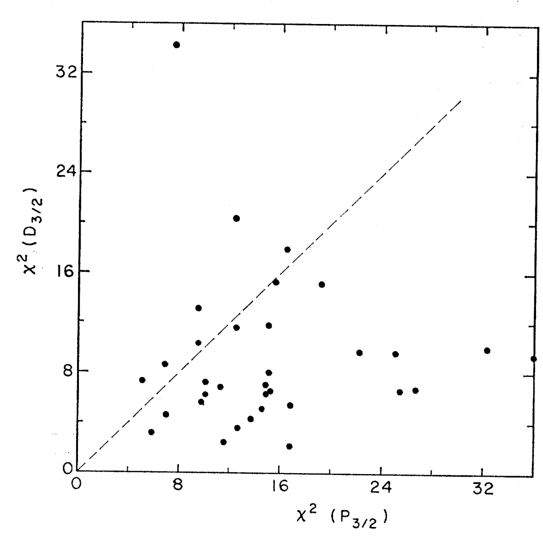


FIG. 5. The parity $\chi^2$ evaluations of two sets of randomly generated events have been combined (in random pairs of $N=25$ and $N=45$ samples). The experimental evaluations (Table II) for forward- and backward-produced $\Xi^*$'s were $\chi^2(D_{3/2})=21.5$ and $\chi^2(P_{3/2})=5.0$. Of the results on the fake data, only one in 33 is worse.

and the even-$L$ moments of the polarization distributions) for strong decay and found them to be consistent with zero.

The conclusions that may be drawn from the $\Xi^*(1530)$ analysis described above are (a) the spin must be greater than $\frac{1}{2}$, but need not be more than $\frac{3}{2}$, and (b) the $\Xi^*$ parity is that of a $P_{3/2}$ (or $D_{5/2}$) state rather than of a $D_{3/2}$ (or $F_{5/2}$) state. The comparison of the spin $\chi^2$ values of Table II with the distributions of Fig. 3 and also the comparison of the $P_{3/2}$ and $D_{5/2}$ curves of Fig. 2 support statement (a). Examination of the parity $\chi^2$'s of Table II (in comparison with Figs. 4 and 5) indicates that the $D_{3/2}$ hypothesis is discriminated against with perhaps a $\leqslant 3\%$ confidence level and thus supports statement (b).

We express appreciation for contributions made by other members of the Alvarez group in the acquiring and processing of the data discussed here. We thank in particular Deane W. Merrill for his interest in the final stages of analysis.

PHYSICAL REVIEW VOLUME 142, NUMBER 4 FEBRUARY 1966

# $\pi$-Pair Photoproduction below 1 BeV*

J. V. Allaby,† H. L. Lynch, and D. M. Ritson
*High-Energy Physics Laboratory, Stanford University, Stanford, California*
(Received 11 October 1965)

Measurements of the differential cross section for the reaction $\gamma+p\rightarrow\pi^-+\pi^++p$ have been made at several angles for photon energies in the range 550–1000 MeV, using the Stanford Mark III linear accelerator. The $\pi^-$ were detected and momentum-analyzed using a 90° magnetic spectrometer. It was found that the reaction was dominated by the quasi-two-body photoproduction $\gamma+p\rightarrow\pi^-+N^*$ (1238) especially near the threshold for this process. At low momenta, the $\pi^-$ were identified by range. At high momenta ($>250$ MeV/$c$), the contaminating electrons were eliminated by using a lead and scintillation-counter sandwich system. The yields of both $\pi^-$ and $\pi^+$ from hydrogen were measured, and the normalization was obtained by comparison with the known cross sections for $\gamma+p\rightarrow\pi^++n$. Computer calculations of the shapes of the yield curves expected from two-body and three-body production enabled the data to be separated into the two possible states $\gamma+p\rightarrow\pi^-+N^*$ (1238) and $\gamma+p\rightarrow\pi^-+\pi^++p$. Angular distributions and total cross sections are presented.

## I. INTRODUCTION

THE photoproduction of pion pairs from protons was first observed by detecting negative pions emitted from a hydrogen target placed in the bremsstrahlung beam of the California Institute of Technology synchrotron.[1–3] This effect was confirmed at Stanford by Friedman and Crowe.[4]

The first detailed study of the reaction producing the negative pions, $\gamma+p\rightarrow\pi^-+\pi^++p$, was carried out by Bloch and Sands[5,6] at the California Institute of Technology. They detected the $\pi^-$ with a magnetic spectrometer and used measurements of single $\pi^+$ photoproduction to normalize the $\pi^-$ yield. We have adopted the same technique, but the high intensity of the Stanford Mark III linear accelerator has enabled us to obtain much more data and to analyze in detail the shapes of the bremsstrahlung yield curves, giving information on the final state.

A group at Cornell also studied the photoproduction of pion multiplets using a hydrogen-filled diffusion cloud chamber.[7,8] In this work, the dominant process was found to be $\gamma+p\rightarrow\pi^-+\pi^++p$, and this reaction was analyzed and total cross sections for incident photon energies in the range 400–1000 MeV were obtained. The detailed analysis of this reaction led to the conclusions that the $\pi^+$ and $\pi^-$ play markedly different roles so that the process could not be described by a simple statistical model and that an appreciable fraction of the final state was reached by formation of the two-body system $\pi^-+N^*$ (1238) with subsequent decay of the $N^*$ into $\pi^++p$.

These conclusions were the motivation for our study of this process in further detail, and our analysis of the shape of the $\pi^-$ yield curves has allowed us to separate out the two-body channel and obtain angular distributions of the $\pi^-$ in the center of mass for the reaction $\gamma+p\rightarrow\pi^-+N^*(1238)$.

* Research supported by the U. S. Office of Naval Research under Contract Nonr 225 (67).
† Present address: CERN, Geneva, Switzerland.
[1] V. Z. Peterson and I. G. Henry, Phys. Rev. **96**, 850 (1954).
[2] M. Sands, M. Bloch, J. G. Teasdale, and R. L. Walker, Phys. Rev. **99**, 652 (1955).
[3] V. Z. Peterson, Bull. Am. Phys. Soc. Ser. II, **1**, 173 (1956).
[4] R. M. Friedman and K. M. Crowe, Phys. Rev. **105**, 1369 (1957).
[5] M. Bloch and M. Sands, Phys. Rev. **108**, 1101 (1957).
[6] M. Bloch and M. Sands, Phys. Rev. **113**, 305 (1959).
[7] J. M. Sellen, G. Cocconi, V. T. Cocconi, and E. L. Hart, Phys. Rev. **113**, 1323 (1959).
[8] B. M. Chasan, G. Cocconi, V. T. Cocconi, R. M. Schectman, and D. H. White, Phys. Rev. **119**, 811 (1960).