considered the degree to which the probability for $K^+ \to \pi^+ + \pi^- + e^+ + \nu$ would be enhanced by final-state pion-pion interactions. Since a total of (2 or 3) $\times 10^3$ τ^+ events have been examined by various observers to date with varying degrees of analysis, the experimental observation of a single $K^+ \to \pi^+ + \pi^- + e^+ + \nu$ is in reasonable agreement with the above theoretical predictions.

In our opinion, the observed event is most likely $K^+ \to \pi^+ + \pi^- + e^+ + \nu$. Behrends and Sirlin[8] have suggested looking for the decay mode $K^+ \to \pi^+ + \pi^+ + e^- + \tilde{\nu}$ as an unambiguous violation of the $\Delta S = \Delta Q$ rule. The present event is in agreement with the rule.

*Work supported in part by grants from the National Science Foundation and the American Academy of Arts and Sciences and by an equipment loan contract with the Office of Naval Research.

[1]G. Harris, J. Orear, and S. Taylor, Phys. Rev. 106, 327 (1957).

[2]W. H. Barkas and D. M. Young, University of California Radiation Laboratory Report UCRL-2759 Rev. (unpublished).

[3]See G. Danby et al., Phys. Rev. Letters 9, 36 (1962) for experimental verification of the existence of two kinds of neutrinos and also for numerous references to theoretical papers on the two-neutrino hypothesis.

[4]K. Chadan and S. Oneda, Phys. Rev. Letters 3, 292 (1959).

[5]V. S. Mathur, Nuovo cimento 14, 1322 (1959).

[6]K. Chadan and S. Oneda, Phys. Rev. 119, 1126 (1960).

[7]G. Ciocchetti, Nuovo cimento 25, 385 (1962).

[8]R. E. Behrends and A. Sirlin, Phys. Rev. Letters 8, 221 (1962).

ON THE SPIN OF THE K^* RESONANCE†

William Chinowsky, Gerson Goldhaber, Sulamith Goldhaber, Wonyong Lee,‡ and Thomas O'Halloran
Physics Department and Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received September 4, 1962)

The production of the K^* resonance[1] in the reaction[2] $K^+ + p \to K^* + N_{33}^*$ at 1.96 BeV/c has permitted us to identify the K^* as a vector meson. Following a method due to Adair,[3] we examined the distribution in the angle α between the outgoing K^+ meson in the K^* c.m. system and the incident K^+ direction. We find a strong anisotropy which can be fitted with $\cos^2\alpha$, and hence conclude that the spin[4,5] of the K^* is ≥ 1. Alston et al. presented evidence for the K^* spin to be less than two within three standard deviations.[1] This result, combined with the present data, allows us to assign spin one to the K^*.[6] It thus follows that the KK^* relative parity is even. For odd $K\Lambda N$ parity[7] this leads to the spin and parity assignment 1^- for the K^*.

The experiment was carried out with the 20-inch Brookhaven bubble chamber[8] in a separated beam[9] tuned to K^+ mesons.

The reaction we have studied is

$$K^+ + p \to K^+ + \pi^- + p + \pi^+. \qquad (1)$$

This reaction, which amounts to about 10% of the total cross section, has the property that a large proportion of events occur in the double resonant state

$$K^+ + p \to K^{*0} + N_{33}^{*++}, \quad K^{*0} \to K^+ + \pi^-, \quad N_{33}^{*++} \to p + \pi^+. \qquad (2)$$

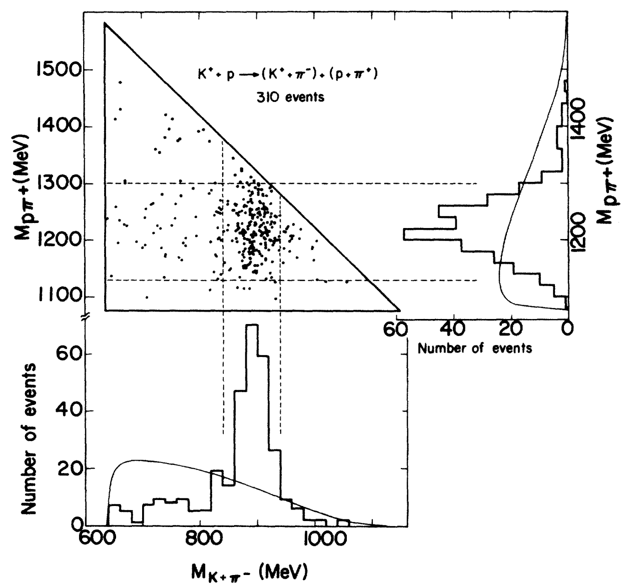

FIG. 1. Scatter diagram of the effective-mass distribution $M_{p\pi^+}$ versus $M_{K^+\pi^-}$. The triangle delineates the kinematical limits. The projections on the $M_{p\pi^+}$ mass axis show the N_{33}^* production, while the projection on the $M_{K^+\pi^-}$ axis shows the simultaneous K^* production. The curves give the distributions expected from phase-space calculations without dynamic effects.

The evidence for Reaction (2) is shown in Fig. 1, where we present a plot of the effective mass distribution $M_{p\pi^+}$ against $M_{K^+\pi^-}$. The triangle shown in the figure gives the kinematic mass limits for the two-particle states $K\pi$ and $p\pi$. It should be noted that this is not a "uniform-density surface" in phase space. The projections on the two mass axes are also shown in the figure. Here we have defined events with effective mass 840 $\leq M_{K^+\pi^-} \leq$ 940 MeV as lying within the K^* resonance and events with 1130 $\leq M_{p\pi^+} \leq$ 1300 MeV as lying within the N_{33}^* resonance. These mass limits correspond roughly to a level of 10% of the respective peak values. To date we have completed the analysis[10] of about 80% of our available data, namely, 310 events. Of these, 201 events lie within both of the above mass limits, i.e., within the "double resonance region." In what follows, we confine our discussion to these latter events, which can then be considered as examples of a "two-particle" reaction, as given in (2).

We observe that the production angle of the K^* is strongly peaked forward, as shown in Fig. 2. Here θ_{K^*} is the angle between the incident K^+ meson and the outgoing K^* in the K^+-p c.m. system.

In order to perform an "Adair analysis," we now limit ourselves further to those events for which $1.0 \geq \cos\theta_{K^*} \geq 0.8$. There are 69 such events in our sample. In Figs. 3(a) and 3(b) we present the unfolded and folded distributions in in the K^* decay angle, α, defined above. The

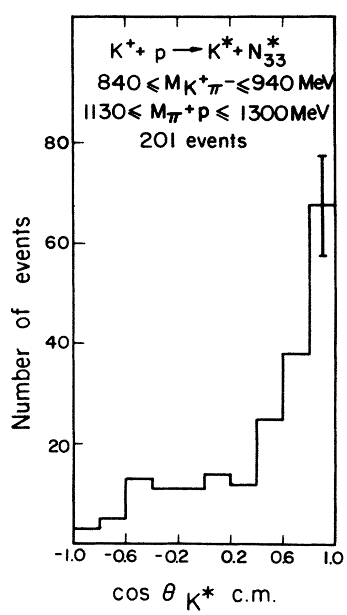

FIG. 2. The angular distribution for K^* production. The events shown here are chosen to lie inside both the N^* and K^* resonances.

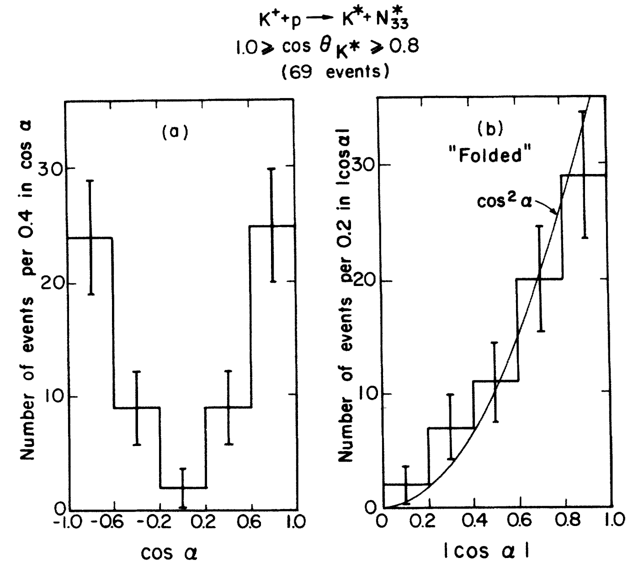

FIG. 3. The angular distribution of α, the angle of the outgoing K^+ in the K^* c.m. system with respect to the incident K^+ direction. The 69 events shown are selected to lie inside the N^* and K^* resonances.

anisotropy of the distribution immediately rules out a spin-zero assignment for the K^*. In the decay of a spin-one K^*, the angular distribution depends on the state of alignment of the K^* spin as determined by the dynamics of the production reaction. For the cases of maximal alignment of the spin vector with respect to the incident direction, the distributions would have the forms given in Table I. For a nonaligned spin this distribution would be isotropic. Also given there are the corresponding distributions for the N^* decay. Any combination of the listed distributions is allowed. The observed distribution in the K^* decay angle is fitted well with a pure $\cos^2\alpha$ intensity distribution. In Figs. 4(a) and 4(b) we present the corresponding distributions for the N^* decay angle

Table I. Allowed spin projections on the incident K^+p axis of a spin-one K^* and the N_{33}^* for an initial proton spin projection of $m = \frac{1}{2}$. The corresponding angular distributions for the K^* decay angle, α, and the N^* decay angle, β, are also given.

$m_s(K^*)$	$m_s(N^*)$	$I(\alpha)$	$I(\beta)$
+1	$-\frac{1}{2}$	$\frac{1}{2}\sin^2\alpha$	$1+3\cos^2\beta$
0	$+\frac{1}{2}$	$\cos^2\alpha$	$1+3\cos^2\beta$
-1	$+\frac{3}{2}$	$\frac{1}{2}\sin^2\alpha$	$3\sin^2\beta$

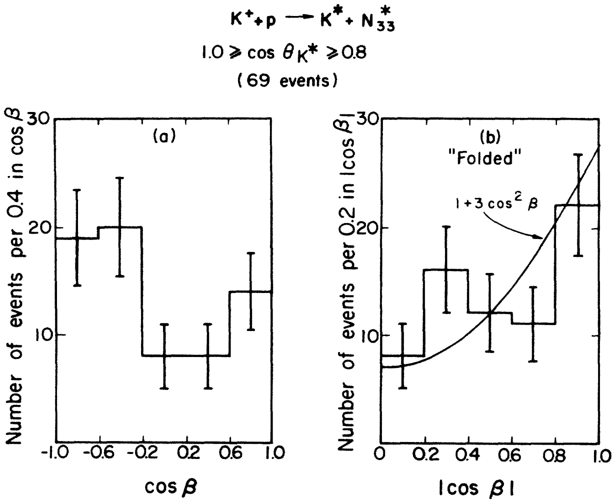

FIG. 4. The angular distribution of β, the angle of the outgoing proton in the N^* c.m. system with respect to the incident K^+ direction. The same events described in Fig. 3 are shown here.

β. For a completely aligned N^* with $m_s(N^*)=\pm\frac{1}{2}$, and if all partial wave amplitudes other than P wave are negligible, the predicted distribution is $1+3\cos^2\beta$. Such a fit is consistent[11] with our data.

These distributions thus imply a strong alignment of the K^* spin, with the component $m_s(K^*)=0$ along the incident beam direction. It is perhaps worth noting that just such an alignment would result if the one-pion exchange were a dominant contributor to the production reaction. This can be seen by noting that for events with $\cos\theta_{K^*}\geq 0.8$, the angle α differs little from the $K\pi$ scattering angle at the K^* vertex. At that vertex the K^* spin can have only the projection $m_s(K^*)=0$ on the "incident" K-π axis, since here we are dealing with two spin-zero "incident" particles. Hence the projection on the incident beam direction (i.e., K-p axis) is also zero, which then results in a $\cos^2\alpha$ distribution.

We wish to take this opportunity to thank the many members of the staff of the Brookhaven National Laboratory for their very helpful attitude in making this experiment possible. In particular, we would like to express our appreciation to Dr. Hildred Blewett, Dr. Hugh Brown, Dr. Ralph Shutt, Dr. James Sanford, Mr. Julius Spiro, Dr. Medford Webster, Dr. Ed Hart, and the AGS operating crew.

We also wish to thank Dr. Samuel Berman, Dr. Gyo Takeda, and Dr. Charles Zemach for a number of helpful discussions. Finally, this work would not have been possible without the active help and interest of our scanning, measuring and computing personnel.

---

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

‡Present address: Physics Department, Columbia University, New York, New York.

[1]M. H. Alston, L. W. Alvarez, P. Eberhard, M. L. Good, W. Graziano, H. K. Ticho, and S. G. Wojcicki, Phys. Rev. Letters 6, 300 (1961).

[2]W. Chinowsky, G. Goldhaber, S. Goldhaber, W. Lee, and T. O'Halloran, in Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN, Geneva, Switzerland, to be published); Lawrence Radiation Laboratory Report UCRL-10337, 1962 (unpublished).

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

[4]R. Armenteros, L. Montanet, D. R. O. Morrison, A. Shapira, S. Nilsson, J. Vandermeulen, Ch. D'Andlau, A. Astier, C. Ghesquiere, B. P. Gregory, D. Rahm, P. Rivet, and F. Solmitz, in Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN, Geneva, Switzerland, to be published); CERN/TC/PHYSICS 62-9 (unpublished).

[5]M. H. Alston, G. R. Kalbfleisch, H. K. Ticho, and S. G. Wojcicki, in Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN, Geneva, Switzerland, to be published); Lawrence Radiation Laboratory Report UCRL-10232, 1962 (unpublished).

[6]At the 1962 International Conference on High-Energy Nuclear Physics at CERN, evidence was presented in favor both of K^* spin ≥ 1 (reference 4) and of spin 0 (reference 5).

[7]M. Block, F. Anderson, A. Pevsner, E. Harth, J. Leitner, and H. Cohn, Phys. Rev. Letters 3, 291 (1959).

[8]R. I. Louttit, in Proceedings of the International Conference on Instrumentation for High-Energy Physics, Berkeley, California, September, 1960 (Interscience Publishers Inc., New York 1961), p. 117.

[9]C. Baltay, J. Sandweiss, J. Sanford, H. Brown, M. Webster, and S. Yamamoto, in Proceedings of the High-Energy Instrumentation Conference, CERN, 1962 (to be published).

[10]In this work we utilized a modification of the geometrical reconstruction (PANG) and kinematical fitting (KICK) programs of the Alvarez Group. J. P. Berge, F. T. Solmitz, and H. D. Taft, Rev. Sci. Instr. 32, 538 (1961); A. H. Rosenfeld and J. M. Snyder, Rev. Sci. Instr. 33, 181 (1962).

[11]For a $1+3\cos^2\beta$ fit we obtain $\chi^2=7.0$. Within the limited statistics other forms of the distribution in $\cos\beta$ cannot be ruled out. An isotropic distribution in β, for instance, yields $\chi^2=6.5$.