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Submitted to Physical Review Letters

UCRL-18640
Preprint

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

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ABSTRACT

Predictions of the quark model of high-energy scattering are tested by using the reaction $K^- p \to \bar{K}^* \Delta$. All predictions are satisfied when interpreted as applying in the t-channel coordinate system.

The joint decay angular distribution in $K^- p \to K^* \Delta$ is used to test predictions derived from the quark model of high-energy scattering by Bialas and Zalewski.[1] These authors have assumed the additivity of the quark-quark scattering amplitudes, and have classified their predictions into three groups, each progressively more restrictive in additional assumptions concerning equalities among certain quark-quark spin-flip amplitudes.

We find the data in excellent agreement with the predictions of the first two classes. For the third class the coordinate system in which the predictions are expected to hold is not specified by the model. We find the data in satisfactory agreement with these predictions in the t-channel coordinate system[2] but not in the helicity coordinate system.[3]

The reaction $K^- p \to \bar{K}^* \Delta$ is studied in this experiment by an analysis of the reaction $K^- p \to p \bar{K}^0 \pi^0 \pi^-$. Events were obtained from an exposure of the

Lawrence Radiation Laboratory 72-inch hydrogen bubble chamber to a separated K^- beam from the Bevatron in the momentum interval 2.1 to 2.7 GeV/c.[4] The results reported here were obtained in the higher-momentum part of the exposure--2.58, 2.61, and 2.7 GeV/c--with an equivalent path-length of 12.8 eV/μb. Approximately 3300 examples of this reaction survived cuts in fiducial volume and of short-length $\overline{K}^0$.

The joint decay angular distribution for $K^* \Delta$ in coordinate systems with spin-quantization axes in the production plane may be written[5,6]

$$I(\Omega_1\Omega_2) = \frac{1}{16\pi^2} \sum_{\substack{\ell_1=0,2\\ \ell_2=0,2}} \sum_{m_1=0}^{\ell_1} \sum_{m_2=0}^{\ell_2} R^{\ell_1\ell_2}_{m_1m_2} \operatorname{Re} Y^{\ell_1}_{m_1}(\Omega_1) \operatorname{Re} Y^{\ell_2}_{m_2}(\Omega_2) + I^{\ell_1\ell_2}_{m_1m_2} \operatorname{Im} Y^{\ell_1}_{m_1}(\Omega_1) \operatorname{Im} Y^{\ell_2}_{m_2}(\Omega_2), \tag{1}$$

where ℓ_1, m_1, and Ω_1 refer to the $\overline{K}^*$ decay and ℓ_2, m_2, and Ω_2 to the Δ. $Y^{\ell}_m(\Omega)$ is a spherical harmonic function. The 15 $R^{\ell_1\ell_2}_{m_1m_2}$ (Ref.7) and 4 $I^{\ell_1\ell_2}_{m_1m_2}$ decay parameters reflect the spin orientations of the $\overline{K}^*$ and Δ, which in turn depend upon the dynamics of the production process. The most serious problem in measuring these decay parameters is the impossibility of obtaining a pure sample of $K^*\Delta$ events in the $p\overline{K}^0\pi^0\pi^-$ final state. Most of the background comes from other unassociated resonance production. In order to minimize background effects, only those events for which $BW(\Delta)\, BW(\overline{K}^*) > 0.2$ were used for the $\overline{K}^*\Delta$ decay analysis. BW is a normalized[8] Breit-Wigner function of the $p\pi^0$ and $\overline{K}^0\pi^-$ invariant masses.[9]

The amplitudes responsible for the production of the background events may interfere with the $\overline{K}^*\Delta$ production amplitudes. Tests were made

for this effect by utilizing the rapid phase variation of the Breit-Wigner amplitude. The $\overline{K}^*\Delta$ events were divided into several samples with very different phases for the $\overline{K}^*\Delta$ amplitude. The moments of the 19 decay-angle functions appearing in Eq. (1) were evaluated for these samples. Any significant interference would cause the moments evaluated for different samples to be quite different. Within the statistics of this experiment no difference was detected between corresponding moments evaluated for the different samples.

Noninterfering background effects were taken into account by assuming that the final-state interactions can be described by an incoherent sum of resonant amplitudes and Lorentz-invariant phase space. The frequency function for each event according to this model has the form

$$f = \alpha_{\overline{K}^*\Delta} \frac{BW(\overline{K}^*)BW(\Delta)}{\int BW(\overline{K}^*)BW(\Delta)d\rho} I(\Omega_1\Omega_2) + \sum \frac{\alpha_i BW_i}{\int BW_i d\rho} + \frac{1-\alpha_{\overline{K}^*\Delta}-\Sigma\alpha_i}{\int d\rho}, \qquad (2)$$

where α_i is the relative rate for the production of the ith resonance process, and BW_i is a Breit-Wigner function of the mass, width, and invariant mass of the decay products. The integrals in the denominator normalize the frequency function so that α_i is the fraction of the ith process in the final state; $d\rho$ is a volume element of phase space. The first term in Eq. (2) represents the contribution to the final state from $\overline{K}^*\Delta$ production, which is given a joint decay angular distribution $I(\Omega_1\Omega_2)$ described by Eq. (1). The second term is the contribution of all the other resonant processes in the final state, and the last term represents the nonresonant events.

Taking Eq. (2) as a probability density, one obtains for the moment of an angular function, $Z(\Omega_1\Omega_2)$, appearing in Eq. (1):

$$\langle Z^{\ell_1\ell_2}_{m_1m_2} \rangle = \int Z^{\ell_1\ell_2}_{m_1m_2} \, f \, d\rho \Big/ \int f \, d\rho$$

$$= \alpha_{\overline{K}^*\Delta} \, X^{\ell_1\ell_2}_{m_1m_2} \int (Z^{\ell_1\ell_2}_{m_1m_2})^2 \, d\Omega_1 d\Omega_2 + \sum \alpha_i \frac{\langle BW_i Z^{\ell_1\ell_2}_{m_1m_2} \rangle}{\int BW_i \, d\rho} , \tag{3}$$

where X = R or I depending upon which angular function Z is chosen. Solving for $X^{\ell_1\ell_2}_{m_1m_2}$, one has

$$X^{\ell_1\ell_2}_{m_1m_2} = \frac{\langle Z^{\ell_1\ell_2}_{m_1m_2} \rangle - \sum \alpha_i \dfrac{\langle BW_i Z^{\ell_1\ell_2}_{m_1m_2} \rangle}{\int BW_i d\rho}}{\alpha_{\overline{K}^*\Delta} \int (Z^{\ell_1\ell_2}_{m_1m_2})^2 \, d\Omega_1 \, d\Omega_2} . \tag{4}$$

For a pure $\overline{K}^*\Delta$ sample Eq. (4) reduces to

$$X^{\ell_1\ell_2}_{m_1m_2} = \frac{\langle Z^{\ell_1\ell_2}_{m_1m_2} \rangle}{\int (Z^{\ell_1\ell_2}_{m_1m_2})^2 \, d\Omega_1 d\Omega_2} .$$

Thus the $\alpha_{\overline{K}^*\Delta}$ term in the denominator and the sum in the numerator account for noninterfering background effects.

The $\overline{K}^*\Delta$ decay parameters measured in this experiment were evaluated by employing Eq. (4). The moments $\langle Z^{\ell_1\ell_2}_{m_1m_2} \rangle$ were evaluated by taking the average value of the angular function $Z^{\ell_1\ell_2}_{m_1m_2}(\Omega_1\Omega_2)$ over the events in the sample. The $\alpha_{\overline{K}^*\Delta}$ and α_i were evaluated by maximum-likelihood fitting employing Eq. (2) as the model,[10] with $I(\Omega_1\Omega_2) = 1$.[11] The $\langle BW_i Z^{\ell_1\ell_2}_{m_im_2} \rangle / \int BW_i d\rho$ were calculated by Monte Carlo integration.

Consistency checks were made on the measured parameters; the requirements that the single vertex spin-density matrices have positive eigen-

values and unit trace[12] were satisfied in all measurements. Further constraints imposed by conservation of angular momentum along the incident beam direction for collinear scattering were satisfied by the decay parameters measured in the most forward production-angle bins.[13]

Tests of Class A predictions. Using only the additivity assumption of the quark model, Bialas and Zalewski have derived relations between the decay parameters in double resonance production. Expressed in terms of moments of decay direction cosines these relations are

$$\langle y_1^2 \rangle = 2 \langle y_2^2 \rangle - 1/3,$$
$$\langle y_2^2 (x_1^2 - y_1^2 \rangle = 4/15 \langle x_1^2 - z_1^2 \rangle,$$
$$\langle y_2^2 (x_1 z_1) \rangle = 4/15 \langle x_1 z_1 \rangle,$$
$$\langle y_1^2 (x_2^2 - z_2^2) \rangle = 1/5 \langle x_2^2 - z_2^2 \rangle,$$
$$\langle y_1^2 (x_2 z_2) \rangle = 1/5 \langle x_2 z_2 \rangle,$$
$$\langle y_1^2 y_2^2 \rangle = \frac{51}{90} \langle y_1^2 \rangle - \frac{3}{50},$$

where x_1, y_1, z_1 are the direction cosines for the $\overline{K}^*$ decay evaluated in its rest frame and x_2, y_2, z_2 are direction cosines for the Δ decay. These relations are expected to hold for coordinate systems in which the z axes are in the production plane.

Figure 1 compares our experimental determination of the left- and right-hand sides of these relations for five intervals of production angle. The measurements at all production angles clearly satisfy the Class A relations.

Tests of Class B relations. Demanding equality of two of the four quark-quark spin-flip amplitudes, in addition to additivity, leads to six additional constraints on the $\overline{K}^*\Delta$ decay parameters. Table I lists these Class B relations along with the corresponding measurements in this experiment.

The coordinate system in which these relations are expected to hold is not specified by the model; however, if they are satisfied in any coordinate system, they must hold in all other systems that can be reached by a common rotation of coordinates in both the $\overline{K}^*$ and Δ rest frames. We have tested these relations in the helicity and t-channel coordinate systems. These coordinate systems are not connected by a common rotation, but the difference from a common rotation is small in this reaction. All the measurements of Table I are in agreement with these Class B relations in both coordinate systems.

Tests of Class C relations. Requiring, in addition to the assumptions of Class B, equality of the remaining two quark-quark spin-flip amplitudes gives rise to nine additional constraints among the $\overline{K}^*$ Δ decay parameters. Table II lists these Class C constraints together with the corresponding measurements in this experiment. As for the Class B relations, the model does not specify the coordinate system in which these predictions should hold. Unlike the Class B relations, however, the Class C relations are not invariant to common rotations of coordinates in the $\overline{K}^*$ and Δ rest frames. The results in Table II corresponding to measurements in the t-channel coordinate system are in satisfactory agreement with the predictions, while those of the helicity coordinate system are not. The χ^2 for 18 degrees of freedom in the t-channel and helicity coordinate systems are 18 and 68 respectively.

We acknowledge the support and cooperation of many members of Group A. We thank Professor Luis Alvarez for his continued encouragement and support. We acknowledge with thanks the efforts of the people who helped with the scanning and measuring, and of the 72-inch bubble chamber and Bevatron operating crews.

Footnotes and References

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

1. A. Bialas and K. Zalewski, Nucl. Phys. B6, 465 (1968).

2. The t-channel coordinate system has the beam direction as the axis of quantization for the $\bar{K}^*$ decay in its rest frame and the target direction as the quantization axis for the Δ decay in its rest frame. The y axis in both rest frames is the normal to the production plane defined by $\hat{m} = (\hat{K}^- \times \hat{K}^{*-})/|\hat{K}^- \times \hat{K}^{*-}|$. The x axis is chosen in each rest frame so as to form a right-handed coordinate system.

3. The helicity coordinate system has the line of flight of the $\bar{K}^*$ and Δ as the decay quantization axes. The x and y directions are defined in the same manner as for the t-channel coordinate system.

4. J. J. Murray, J. Button-Shafer, F. T. Shively, G. H. Trilling, J. A. Kadyk, A. Rittenberg, D. M. Siegel, J. S. Linsey and D. Merrill, in Proceedings of the Conference on High Energy Physics, Dubna, 5-15 August 1964.

5. S. M. Berman and R. J. Oaks, Phys. Rev. 135, B1034 (1964).

6. A. Kotanski and K. Zalewski, Nucl. Phys. B4, 559 (1968).

7. There are 16 R-decay parameters; however, normalization of the decay angular distribution requires $R^{00}_{00} = 1$.

8. The Breit-Wigner functions are normalized so that they have the value unity at the resonance mass.

9. With this restriction on the $p\pi^0$ and $\bar{K}^0\pi^-$ invariant masses, background contamination to the $\bar{K}^* \Delta$ sample is 10% in the most forward production-angle intervals increasing monotonically to 50% in the most backward.

10. J. Friedman, MURTLEBERT, A General Program for Fitting Data by the Method of Maximum Likelihood, Lawrence Radiation Laboratory Group A programming Note No. P-156, 1967.

11. The values of the maximum-likelihood solution for the relative fractions of the resonance processes were found to be insensitive to the decay angular distribution assumed for the process.

12. P. Minnaert, Phys. Rev. 151, 1306 (1966).

13. J. T. Donohue, CERN Preprint -Ref. Th. 884, Oct. 1967.

Figure Caption

Fig. 1. Experimental test of the Bialas and Zalewski "class A" quark model predictions (Ref. 1), which assume only the additivity of the quark-quark scattering amplitudes. Measurements are made in the T-channel coordinate system (Ref. 2) for five intervals in center-of-mass production cosine.

Table I. Experimental test of the "class B" quark model predictions for the $\bar{K}^*\Delta$ decay parameters in $K^-p \to \bar{K}^{*-}\Delta$ at 2.6 GeV/c. Comparisons are made in both the t-Channel and helicity coordinate systems for two intervals in center-of-mass production cosine.

Class B relation	t-Channel LHS	t-Channel RHS	Cos θ interval	Helicity LHS	Helicity RHS
$R^{20}_{00} = 2R^{02}_{00}$	0.41±0.07	0.44±0.16	1 to 0.9	0.20±0.07	0.24±0.14
	0.28±0.08	0.30±0.16	0.9 to 0.6	-0.17±0.08	-0.36±0.16
$R^{20}_{20} = 2R^{02}_{02}$	-0.13±0.08	-0.02±0.20	1 to 0.9	0.03±0.09	0.12±0.20
	-0.06±0.10	-0.22±0.22	0.9 to 0.6	0.26±0.11	0.30±0.24
$R^{20}_{10} = 2R^{02}_{01}$	-0.16±0.11	-0.02±0.20	1 to 0.9	-0.44±0.10	-0.46±0.20
	0.16±0.12	-0.24±0.22	0.9 to 0.6	-0.37±0.11	-0.10±0.22
$R^{22}_{02} = R^{22}_{20}$	0.01±0.10	-0.16±0.10	1 to 0.9	0.02±0.11	0.23±0.10
	0.06±0.10	-0.04±0.11	0.9 to 0.6	0.10±0.12	0.13±0.10
$R^{22}_{01} = R^{22}_{10}$	0.00±0.11	-0.12±0.12	1 to 0.9	-0.02±0.11	-0.14±0.11
	-0.10±0.11	-0.11±0.14	0.9 to 0.6	0.18±0.11	0.13±0.11
$R^{22}_{21} = R^{22}_{12}$	0.13±0.11	-0.12±0.15	1 to 0.9	0.21±0.14	-0.12±0.13
	-0.01±0.13	0.09±0.18	0.9 to 0.6	-0.10±0.15	-0.30±0.18

Table II. Experimental test of the "class C" quark model predictions for the $\bar{K}^* \Delta$ decay parameters.

Decay parameter	t-Channel cosθ interval		Helicity cos θ interval	
	1 to 0.9	0.9 to 0.6	1 to 0.9	0.9 to 0.6
Decay parameters predicted to be zero				
R^{20}_{10}	-0.15±0.11	0.16±0.12	-0.44±0.10	-0.37±0.11
R^{02}_{01}	-0.01±0.10	-0.12±0.11	-0.23±0.10	-0.05±0.11
R^{22}_{10}	-0.12±0.12	-0.11±0.14	-0.14±0.11	0.13±0.11
R^{22}_{01}	0.00±0.11	-0.10±0.11	-0.02±0.11	0.18±0.11
R^{22}_{12}	-0.12±0.15	0.09±0.18	-0.12±0.13	-0.30±0.18
R^{22}_{21}	0.13±0.11	-0.01±0.13	0.21±0.14	-0.10±0.15
I^{22}_{12}	-0.10±0.14	0.12±0.16	-0.24±0.14	-0.43±0.16
I^{22}_{21}	-0.14±0.13	0.16±0.14	-0.37±0.14	-0.25±0.16
$R^{22}_{22} = \frac{1}{10}\left(\frac{3}{2}\right)^{1/2} - \frac{1}{2} R^{22}_{22}$				
R^{22}_{22}	0.26±0.11	0.20±0.15	0.13±0.10	0.12±0.17
$\frac{1}{10}\left(\frac{3}{2}\right)^{1/2} - \frac{1}{2} R^{22}_{00}$	0.01±0.04	0.07±0.05	0.17±0.04	0.10±0.04

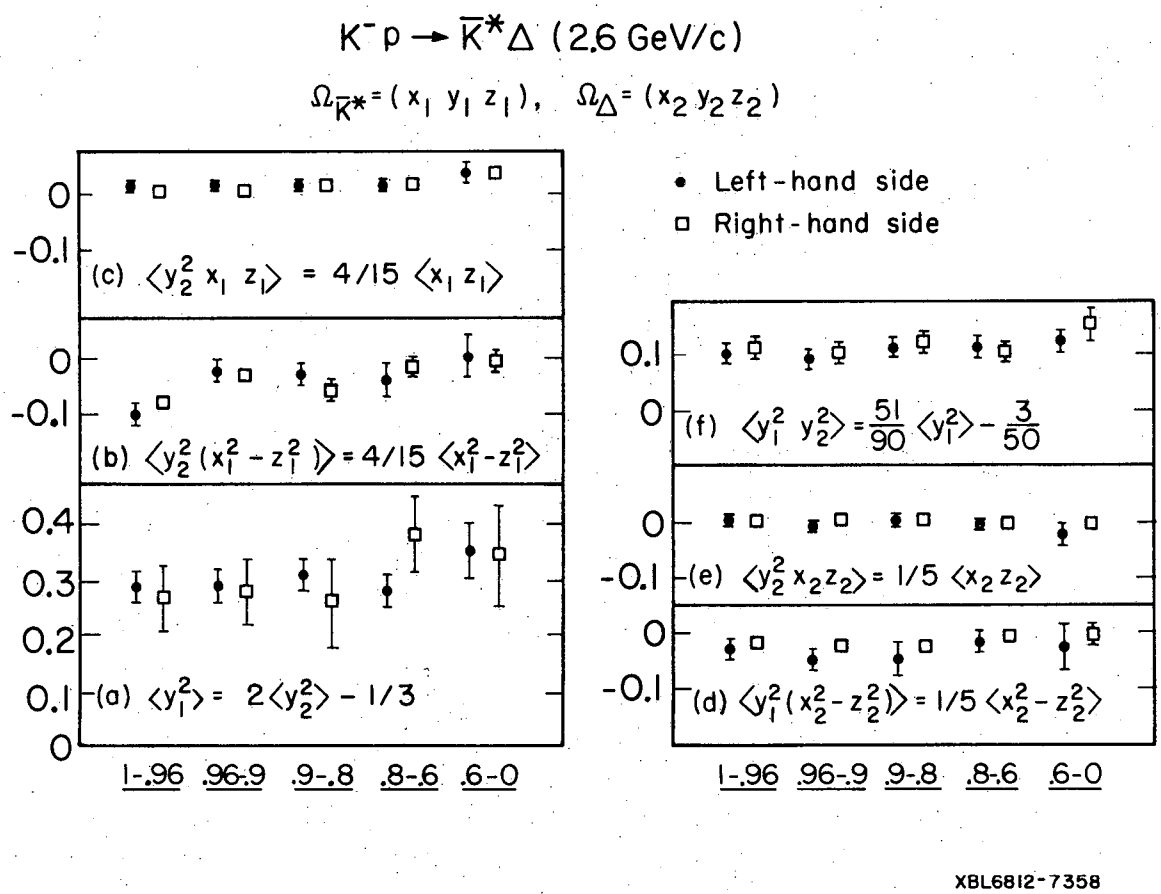
$K^- p \rightarrow \bar{K}^* \Delta$ (2.6 GeV/c)
$\Omega_{\bar{K}^*} = (x_1\ y_1\ z_1)$, $\Omega_\Delta = (x_2\ y_2\ z_2)$
• Left-hand side
□ Right-hand side
(c) $\langle y_2^2\ x_1\ z_1 \rangle = 4/15\ \langle x_1\ z_1 \rangle$
(b) $\langle y_2^2 (x_1^2 - z_1^2) \rangle = 4/15\ \langle x_1^2 - z_1^2 \rangle$
(a) $\langle y_1^2 \rangle = 2 \langle y_2^2 \rangle - 1/3$
(f) $\langle y_1^2\ y_2^2 \rangle = \frac{51}{90} \langle y_1^2 \rangle - \frac{3}{50}$
(e) $\langle y_2^2\ x_2 z_2 \rangle = 1/5\ \langle x_2\ z_2 \rangle$
(d) $\langle y_1^2 (x_2^2 - z_2^2) \rangle = 1/5\ \langle x_2^2 - z_2^2 \rangle$
1-.96 .96-.9 .9-.8 .8-.6 .6-0
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Fig. 1

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