the heavy cosmic rays have lifetimes less than 10^7 yr, too short for completion of the Pb peak from radioactive decay of transbismuth nuclei. (3) Within our limited statistics, in the energy interval ~0.5 to 1 GeV/amu the abundance ratio of extremely heavy nuclei to the Fe-group nuclei is similar to that at higher energies. (4) Previous assignments of charges to relativistic nuclei by both plastics and emulsions are basically correct, though somewhat uncertain because of uncertainty in velocity. (5) Unless there is an unpredictable mixture of neutron-rich and neutron-poor nuclides, we believe we have demonstrated resolution of $\Delta Z \approx \pm 1$. In future flights with a larger area-time factor we are confident that as statistics accumulate, abundance peaks of high-Z nuclei will be recognizable.

We wish to thank T. Clausen for experimental assistance.

†Work supported by the U. S. Atomic Energy Commission under Contract No. AT(04-3)-34, by the National Science Foundation under Grant No. GA 23930, and by the Science Research Council and the Royal Society of London.

*Present address: Dublin Institute for Advanced Studies, Dublin, Ireland.

‡Present address: University of California, Berkeley, Calif. 94720.

[1]P. H. Fowler, J. M. Kidd, and R. T. Moses, Proc. Roy. Soc., Ser. A 318, 1 (1970).

[2]P. B. Price, P. H. Fowler, J. M. Kidd, E. J. Kobetich, R. L. Fleischer, and G. E. Nichols, Phys. Rev. D (to be published).

[3]R. L. Fleischer, P. B. Price, R. M. Walker, M. Maurette, and G. Morgan, J. Geophys. Res. 72, 355 (1967).

[4]D. J. Barber, I. Hutcheon, P. B. Price, R. S. Rajan, and H. R. Wenk, Proceedings of Apollo 12 Lunar Science Conference, Houston, Texas, 11-14 January 1971 (to be published).

[5]P. B. Price, R. L. Fleischer, D. D. Peterson, C. O'Ceallaigh, and D. O'Sullivan, Phys. Rev. Lett. 21, 630 (1968).

[6]D. D. Peterson, Rev. Sci. Instrum. 41, 1254 (1970).

[7]The charge assignments are rather insensitive to the precise form of the relation for effective charge, because this relation also enters into the range-energy calculation in a compensating way.

[8]R. M. Sternheimer, Phys. Rev. 103, 511 (1956).

[9]R. Katz and E. J. Kobetich, Phys. Rev. 186, 344 (1969).

[10]L. V. Spencer, private communication.

Investigation of the Forward Structure in Charge-Exchange $K^{*0}(890)$ Production*

M. Aguilar-Benitez, V. E. Barnes,† D. Bassano, R. L. Eisner, J. B. Kinson,‡ and N. P. Samios
Brookhaven National Laboratory, Upton, New York 11973

(Received 14 December 1970)

We present an investigation of the reaction $K^-p \to K^{*0}(890)n$ at 3.9 and 4.6 GeV/c incident momenta. The order-of-magnitude increase in statistics with respect to previous analysis allows an investigation of the $K^{*0}(890)$-production properties in the very forward region of momentum transfer and also provides a quantitative test of the absorption-modified one-pion exchange model. This model gives an excellent description of the differential cross sections and decay correlations at the two energies.

Numerous models have been proposed to explain hadron interactions.[1] Each has had limited success with the common feature that data are fitted quite well in certain reactions and poorly in others. In particular, production of particles in the extreme forward direction, whether photoproduced or meson produced, has served as a sensitive test of these theories. Currently a great deal of interest has focused on charge-exchange vector-meson production. Analysis[2] of ρ^0 production via the reaction $\pi^-p \to \rho^0 n$ has been rather thorough; comparable data on $K^{*0}(890)$ production has not been available. The present experiment, which investigates the final state $K^-p \to K^{*0}(890)n$, negates this deficiency with at least an order-of-magnitude increase in data. This, and the fact that it is a neutron and not a proton recoiling, allows us to investigate the structure in the region of momentum transfer to the $K^{*0}(890)$ less than m_π^2. We find no strong forward structure (i.e., steep increases or dips) in the differential cross sections or diagonal elements of the density matrix at both 3.9 and 4.6 GeV/c. In addition, the present statistics allow us to make a quantitative test of the absorption model due to Gottfried and Jackson,[3] which is known to be successful in describing ρ^0 production via pseudoscalar exchange. The excellent agreement between this

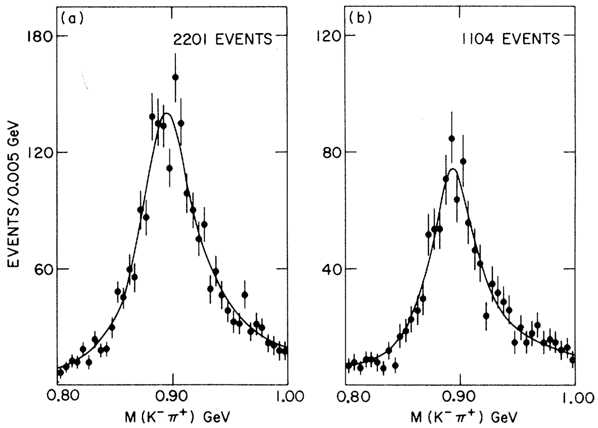

FIG. 1. (a) $K^-\pi^+$ effective-mass distribution from Reaction (1) at 3.9 GeV/c. The curve is the result of the fit described in the text. (b) Same as (a) but at 4.6 GeV/c.

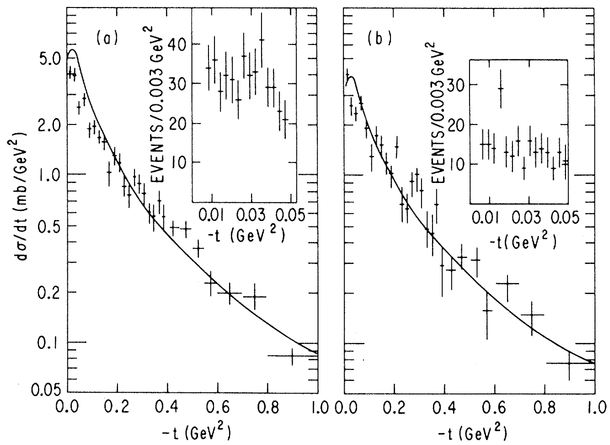

FIG. 2. (a) $d\sigma/dt$ distribution for the reaction $K^-p \to K^{*0}(890)n$ at 3.9 GeV/c. The curve is the result of the OPEA calculation described in the text. The insert shows the momentum transfer distribution in the forward direction in more detail. (b) Same as (a) but at 4.6 GeV/c.

model and the experimental data suggests that absorption-like modification (for instance, Regge cuts) to simple pole models are needed.

The data for this study come from exposures of the Brookhaven National Laboratory (BNL) 80-in. hydrogen bubble chamber to beams of K^- mesons at 3.9 and 4.6 GeV/c incident momenta. The reaction of interest is the one-constraint fit

$$K^-p \to K^-\pi^+n. \tag{1}$$

Events were assigned to this category if the χ^2 probability was greater than 5% and ionization, as measured by the BNL flying-spot digitizer, was consistent with the kinematic interpretation. From a total of ~110 000 two-prong measurements, 9425 fit Reaction (1). Figures 1(a) and 1(b) show the $K^-\pi^+$ effective-mass spectrum from Reaction (1) for the 3.9- (4.6-) GeV/c data. In order to determine the mass, width, and amount of K^{*0}, we have performed a χ^2 fit with a Breit-Wigner shape[4] plus a linear background. The weighted averages over the two momenta are[5]

$$M = 897.8 \pm 0.8 \text{ MeV}, \quad \Gamma = 55.3 \pm 2.6 \text{ MeV}. \tag{2}$$

Figures 2(a) and 2(b) show the momentum transfer ($-t$) distribution between the target proton and the outgoing neutron. The differential cross sections were obtained by fitting each individual $K^-\pi^+$ effective-mass spectrum with the matrix element described above with mass and width fixed at the values given by (2). A good fit to the $d\sigma/dt$ distributions in Figs. 2(a) and 2(b) was achieved using an expression of the form[6] $d\sigma/dt = Ae^{bt+ct^2}$ over the range $0.02 \le -t \le 1.0$ GeV^2. We obtain at 3.9 GeV/c the parameters

$$b = 5.7 \pm 0.1 \text{ GeV}^{-2}, \quad c = 1.9 \pm 0.2 \text{ GeV}^{-4};$$

and at 4.6 GeV/c

$$b = 6.0 \pm 0.5 \text{ GeV}^{-2}, \quad c = 2.2 \pm 0.6 \text{ GeV}^{-4}.$$

The solid curve in the figure represents the absolute prediction of the one-pion exchange model with absorption[3] (OPEA) which, except for the ~20% discrepancy for $|t| < 0.1$ GeV^2, describes the magnitude and structure of the $K^{*0}(890)$-production angular distribution at both energies.[7]

There has been much theoretical debate as to the structure (dip, peak, or flat) of $d\sigma/dt$ for $-t < m_\pi^2$, a region expected, because of the nearness of the pion pole, to be dominated by π exchange. The inserts in Figs. 2(a) and 2(b) show the distribution of $K^{*0}(890)$ events as a function of momentum transfer starting at the kinematic thresholds[8] in bins of 0.003 GeV^2.[9] The data are consistent with a constant cross section from $-t \sim 2m_\pi^2$ to $-t \sim \frac{1}{4}m_\pi^2$. While small forward dips (as predicted by OPEA) or peaks are consistent with the experimental distributions, theoretical models that predict strong forward structure (at least down to $\frac{1}{4}m_\pi^2$) are not consistent with the data.

The investigation of the $K^{*0}(890)$-decay angular distribution (Jackson angle) has shown an asymmetry as previously seen in reactions involving $K^{*0}(890)$ production.[10] As done in the $\pi^-p \to \rho^0 n$ reaction[2] in which an asymmetry in the ρ^0 region is also observed, we have parametrized the decay angular distribution of the $K^-\pi^+$ system in the $K^{*0}(890)$ region[11] in terms of an S-wave background[12] interfering with the P-wave resonance, with the following form:

$$W(\cos\theta,\varphi)=\frac{1}{4\pi}+\frac{3}{4\pi}\{(\rho_{00}-\rho_{11})(\cos^2\theta-\tfrac{1}{3})-\sqrt{2}\,\mathrm{Re}\rho_{10}\sin2\theta\cos\varphi-\rho_{1-1}\sin^2\theta\cos2\varphi\}$$
$$+\frac{\sqrt{3}}{4\pi}\{-2\sqrt{2}\,\mathrm{Re}\rho_{10}{}^{\mathrm{INT}}\sin\theta\cos\varphi+2\,\mathrm{Re}\rho_{00}{}^{\mathrm{INT}}\cos\theta\},$$

applicable in both the Jackson and helicity frames. For the 3.9- and 4.6-GeV/c data combined[13] we have performed a maximum-likelihood fit and determined the values of the density-matrix elements in both the Jackson ($\rho_{ij}{}^J$) and the helicity ($\rho_{ij}{}^H$) frames as a function of the momentum transfer. The ρ_{ij}'s so obtained are given in Fig. 3. The following observations can be made:

(1) In the region $-t<2m_\pi^2$ there is no significant change in either frame of the value for $\rho_{00}-\rho_{11}$ which averages 0.62 (0.58) in the helicity (Jackson) frame. The data in the small $-t$ region rules against any strong variation of ρ_{00} or ρ_{11} down to our kinematic threshold. The large value of $\rho_{00}-\rho_{11}$ suggests the dominance of π exchange.

(2) There is structure in $\rho_{00}-\rho_{11}$ and $\mathrm{Re}\rho_{10}$ from kinematic threshold to about 0.25 GeV^2. Above 0.25 GeV^2 $\rho_{00}{}^J\approx\rho_{11}{}^J$ and $\mathrm{Re}\rho_{10}{}^J\approx 0$ while $\rho_{1-1}{}^J$ increases from ~0.0 to ~0.2. We also note that $\mathrm{Re}\rho_{00}{}^{\mathrm{INT}}$ (which is a measure of the S- and P-wave interference) is zero in the very forward direction, is large for $-t$ between 0.01 and 0.25 GeV^2, and becomes small for large values of $-t$. ${}^J\mathrm{Re}\rho_{00}{}^{\mathrm{INT}}$ is related to the forward (F)-backward (B) asymmetry in the Jackson frame by the relation $\sqrt{3}\,{}^J\mathrm{Re}\rho_{00}{}^{\mathrm{INT}}=(F-B)/(F+B)$. The possibility that we are observing some structure in the forward direction in ${}^J\mathrm{Re}\rho_{00}{}^{\mathrm{INT}}$ makes any simple extrapolation of the forward-backward asymmetry (to extract $K\pi$ S-wave phase shifts) to the pion pole dubious. Correspondingly, the experimentally observed variations of the density-matrix elements as a function of $-t$ would lead one to question the validity of any extrapolation which must assume that only "pion" exchange is present over a large range of momentum transfer.

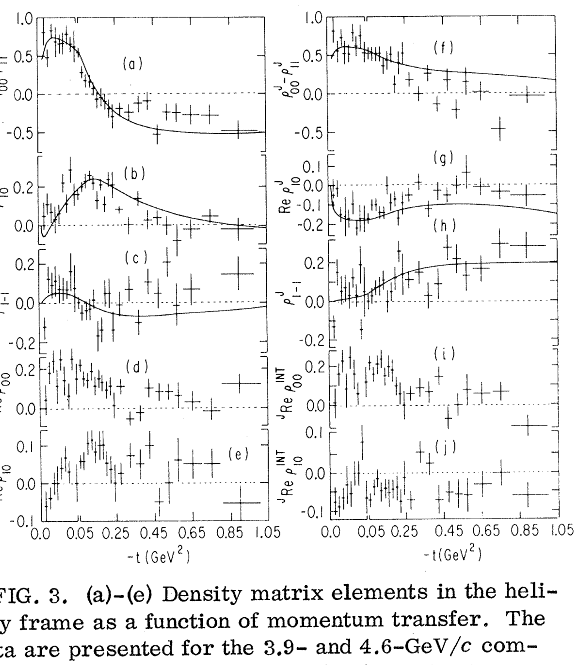

FIG. 3. (a)-(e) Density matrix elements in the helicity frame as a function of momentum transfer. The data are presented for the 3.9- and 4.6-GeV/c combined sample. (f)-(j) Same as (a)-(e) but the density matrix elements are evaluated in the Gottfried-Jackson frame.

The OPEA predictions,[14] represented by the solid curves in Fig. 3, provide a good quantitative description in the small-momentum-transfer region ($-t<0.25$ GeV^2). However, for larger values of $|t|$ (where the model is not expected to be applicable) deviations from the predictions are observed.

In conclusion, in the reaction $K^-p\to K^{*0}(890)n$ at both 3.9 and 4.6 GeV/c, there is no evidence for any significant structure in the differential cross sections and diagonal elements of the density matrix in the very forward direction of momentum transfer. OPEA is seen to provide an excellent description, at small momentum transfers, of the production and decay properties of the $K^{*0}(890)$. As pointed out by Jackson,[1] such good agreement between absorption-model prediction and the experimental distributions would strongly suggest the need for Regge cuts in addition to Regge poles to explain the present data. In particular, Regge pole models (without cuts) invoking the evasive behavior[15] of the pion Regge pole at $t=0$ (which predict dips in the forward direction, $-t<m_\pi^2$) seem to be ruled out by the present investigation.

We thank Dr. G. Kane for suggesting the necessity of exploring the low-t region and for numerous discussions. We acknowledge many helpful discussions with Dr. L. Gutay. We thank the Brookhaven National Laboratory alternating-gradient synchrotron and bubble-chamber staffs for their aid in taking the pictures. The good work in processing the large number of events by our scanning and data personnel is gratefully acknowledged.

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

†Present address: Purdue University, Lafayette, Ind. 47907.

‡Present address: University of Birmingham, Birmingham, England.

[1]See review by J. D. Jackson, Rev. Mod. Phys. 42, 12 (1970).

[2]See, for instance, D. H. Miller *et al.*, Phys. Rev. 153, 1423 (1967).

[3]K. Gottfried and J. D. Jackson, Nuovo Cimento 34, 735 (1964).

[4]We have used a Breit-Wigner shape with energy-dependent width of the form

$$(m/q)\{\Gamma/[(m^2-m_0^2)^2+m_0^2\Gamma^2]\},$$

with $\Gamma=\Gamma_0(q/q_0)^{2l+1}$.

[5]The values obtained at the individual momenta are as follows: at 3.9 GeV/c,

$M=898.7\pm1.0$ MeV, $\Gamma=60.0\pm3.0$ MeV,

$N=2061\pm80$ events, $\sigma=755\pm30$ μb;

at 4.6 GeV/c,

$M=896.2\pm1.3$ MeV, $\Gamma=49.2\pm4.9$ MeV,

$N=905\pm54$ events, $\sigma=534\pm35$ μb.

The cross sections have been corrected for unseen decay modes and probability cuts.

[6]We also performed a fit to the differential cross section using the simple form $d\sigma/dt\sim e^{bt}$. In the momentum-transfer interval $0.02\leq -t\leq 1.0$ GeV^2, we obtained for the parameter b the value 4.2 ± 0.2 (4.5 ± 0.2) at 3.9 (4.6) GeV/c. However, a significantly better agreement with the data was achieved with the fit described in the text.

[7]We have used the following parameters in the OPEA calculation: at 3.9 GeV/c, $\gamma_i=0.043$, $\gamma_f=0.032$, $C_i=0.73$, and $C_f=1.00$; at 4.6 GeV/c, $\gamma_i=0.036$, $\gamma_f=0.027$, $C_i=0.70$, and $C_f=1.00$. The parameter which specifies the elastic-scattering exponential falloff was obtained by fitting our elastic data with the form e^{At} in the region $0.1\leq -t\leq 0.5$ GeV^2. The value obtained at 3.9 and 4.6 GeV/c was $A\sim7.4$ GeV^{-2}.

[8]The lower limits in momentum transfer for the differential cross-section distributions are 0.007 GeV^2 (0.005 GeV^2) at 3.9 GeV/c (4.6 GeV/c). These values have been used in order to avoid biases due to the spread of the $t_{\rm min}$ distributions caused by the finite width of the $K^{*0}(890)$. They correspond to $|t_{\rm min}|$ for a $K\pi$ mass of ~940 MeV.

[9]The resolution obtained from an ideogram of a delta function using errors from the kinematic full error matrix was 0.0005 GeV^2 (full width at half maximum) in the lowest bin of momentum transfer.

[10]See, for instance, T. G. Trippe *et al.*, Phys. Lett. 28B, 203 (1968); J. Goldberg *et al.*, Phys. Lett. 30B, 434 (1969).

[11]The $K^{*0}(890)$ region was defined by 0.84 GeV $\leq M(K^-\pi^+)\leq 0.94$ GeV.

[12]The fits to the $K^-\pi^+$ effective-mass distributions show that the background amounts to less than 7% in the $K^{*0}(890)$ region. The parametrization of the decay correlations for the $K^-\pi^+$ system assumes that this background is entirely S wave and provides an excellent description of the data. This implies that $2\rho_{11}+\rho_{00}$ has an average value of 0.93 over the complete range of momentum transfer.

[13]We have investigated the decay angular distributions for the $K^{*0}(890)$ at 3.9 and 4.6 GeV/c separately, and we found no statistically significant differences between the two energies.

[14]The theoretical curves correspond to pure $K^{*0}(890)$ prediction and do not include a small renormalization effect (averaging ~7%) due to the presence of the $K\pi$ S-wave background.

[15]See the review on conspiracy and evasion by A. Białas, in *Proceedings of the Topical Conference on High-Energy Collisions of Hadrons, CERN, 1968* (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 218.