the momentum range 1.6–2.2 GeV/c.

[14]L. Montanet, in *Proceedings of the Lund International Conference on Elementary Particles,* edited by G. von Dardel (Berlingska-Boktryckeriet, Lund, Sweden, 1970), p. 220. Some of the in-flight results appear unreliable, however; see p. 206.

[15]Here we assume that the width of such an isolated s-channel resonance is less than 300 MeV, the range of c.m. energy under discussion.

[16]The experimental angular distributions are in reasonable accord with this assumption. We are effectively ignoring $I=\frac{5}{2}$ exchange which is either small or forbidden for the reactions of Table II.

[17]This fit also predicts $\sigma(\pi^0\pi^0)=11\pm4$ μb. From $\sigma_{\rm expt}(\pi^+\pi^-)=45\pm3$ μb and $I=\frac{1}{2}$ exchange which seems to dominate the $\pi^+\pi^-$ distribution, we get a (semiexperimental) value of $\sigma(\pi^0\pi^0)=10\pm3$ μb for comparison.

[18]W. W. M. Allison *et al.*, to be published.

Coherent Production of $K^{*-}(890)$ by K^- at 10 and 12.7 GeV/c on $A\approx 20$ Nuclei

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Coherent $K^{*-}(890)$ production by K^- of 10.0 (12.7) GeV/c on $A\approx 20$ nuclei is observed with $\sigma_A=150\pm50$ (131 ± 35) μb/nucleus. The K^* alignment, t' distribution and cross section are consistent with production via isoscalar, natural-parity exchange.

Because exchange of isoscalar trajectories of natural parity contributes to $K^{*-}(890)$ production by K^- beams on free protons,[1] coherent production of $K^*(890)$ on complex nuclei is expected.[2] So far this coherent production has been observed only in deuterium experiments.[3] We report here evidence for coherent $K^*(890)$ production from nuclei with $A\approx 20$.

Our results are based on two bubble-chamber experiments with 10.0- and 12.7-GeV/c K^- beams.[4] The 10.0-GeV/c exposure was made in the CERN 1.2-m heavy-liquid bubble chamber filled with a a propane-freon mixture (atomic composition C:F:Br:H $\approx$ 6:3:1:13). The 12.7-GeV/c exposure was made in the Brookhaven National Laboratory 80-in. chamber filled with a neon-hydrogen mixture (Ne:H $\approx$ 12:7). The two exposures together yield roughly one event per μb of cross section.

The radiation lengths of these liquids are 26 and 44 cm, respectively. This gives a mean probability for detection of both γ's from a π^0 of about 65% for each experiment.

The film was scanned for one-prong events with no indication of nuclear breakup and with any number of V^0's or γ's pointing to the interaction. In order to eliminate spurious γ's (mainly bremsstrahlung) from our sample, cuts on angles between γ's and on γ momenta have been defined from a Monte Carlo study of multi-π^0 events. After these cuts, events belonging to the topologies 1-prong + 1V^0 and 1-prong + 2γ were fitted respectively to the reactions (4C means four-constraint, etc.)

$$K^-X \to \bar{K}^0\pi^-X \quad (4\text{C fit}), \quad \bar{K}^0 \to \pi^-\pi^+ \tag{1}$$

$$K^-X \to K^-\pi^0X \quad (2\text{C fit}), \quad \pi^0 \to \gamma\gamma \tag{2}$$

The resulting fits are insensitive to the mass of X for events with small momentum transfer, t. For large t the neutron mass is appropriate, and we have used it for all production hypotheses.

We have removed from the sample corresponding to Reaction (2) all events which were also compatible with the 5C $K^- \to \pi^-\pi^0$ decay of the K^- beam.

After a probability cut on the kinematic fit [at 0.2% for Reaction (1) and 8% for Reaction (2)], the number of events compatible with Reaction (1) is 42 (72), and with Reaction (2) is 89 (103) at 10.0 (12.7) GeV/c.

Evidence for K^{*-}(890) production in the low-t' region [t' <0.07 (GeV/c)^2].—Figure 1 shows the combined $(\bar{K}\pi)^-$ mass spectrum corresponding to all events, without any weighting between the two reactions or the two energies. The four sub-samples give compatible mass spectra. The t' distribution[5] of events in the K^*(890) region [$(\bar{K}\pi)^-$ invariant mass between 0.8 and 1.0 GeV] is shown in Fig. 2. This spectrum is characterized by an accumulation of events in the region t' <0.07 (GeV/c)^2. If we restrict ourselves to this low-t' region, we obtain the $\bar{K}\pi$ mass spectrum (hatched on Fig. 1) showing a more prominent K^*(890) and an indication of K^*(1400).

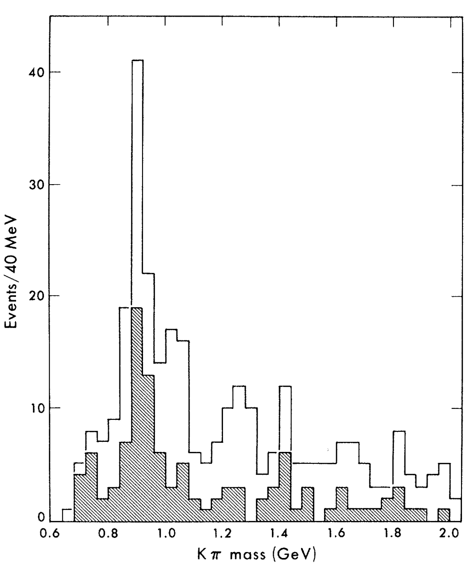

FIG. 1. $K\pi$ mass spectrum. Combined data (302 events) of Reactions (1) and (2) at 10.0 and 12.7 GeV. Cross-hatched histogram is for t'<0.07 GeV/c^2 (109 events).

The t' distribution corresponding to K^* production on free protons is known to have a dip in the forward direction, at least in the 10-GeV/c beam momentum region.[1,6] We expect a similar shape for the incoherent events (produced on quasifree nucleons) present in our data. We have chosen the function $t'e^{-\lambda t'}$ to parametrize this shape, consistent with ω and P' exchange in the reaction $\bar{K}p \to \bar{K}^*p$. Fitting this function to the 10-GeV/c K^-p data[6] for t' <0.3 (GeV/c)^2, we find $\lambda = 10.8 \pm 0.5$ (GeV/c)$^{-2}$ (statistical error only). The "incoherent" curve in Fig. 2 is this function fitted to our data as described below. Figure 2 shows that we have an excess above the incoherent curve of about forty events in the low-t' region.

For assurance that these low-t' events actually correspond to Reactions (1) or (2) from nuclear targets, we have investigated possible sources of background, which are the reactions (a) $K^-X \to K^-\pi^0\pi^0X$, where we missed two γ's; (b) K^-X

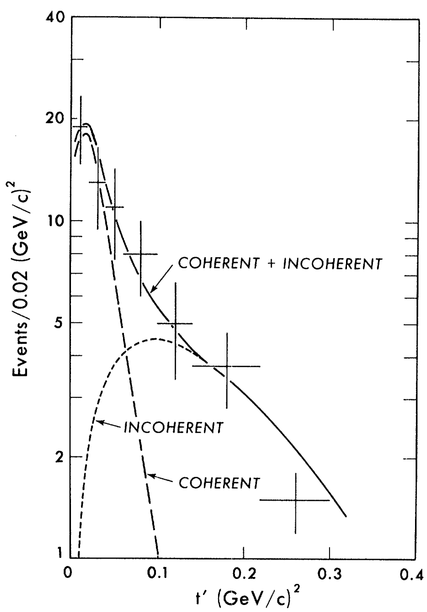

FIG. 2. t' distribution for 90 events in the K^* region ($K\pi$ mass between 0.8 and 1.0 GeV). The "incoherent" curve is the function $t'\exp(-10.8\,t')$, describing K^* production from hydrogen or incoherent K^* production from nuclei. The "coherent" curve is the predicted shape of the coherent K^* production from nuclei as modified by experimental resolution. A good fit (solid curve) to the observed t' distribution for t' < 0.3 GeV/c^2 is obtained by 47 ±9% coherent plus 53% incoherent production.

$\to \bar{K}^0\pi^-\pi^0X$, where we either missed both γ's or missed the $\bar{K}^0$ and misinterpreted the π^- as a K^-; (c) $K^-X \to K^-\pi^0X$, where we missed one of the two γ's and added a spurious γ which evaded the bremsstrahlung cuts; and (d) $K_{\pi 2}$ beam decays for which the 5C decay fit failed. A study of backgrounds (a), (b), and (c) shows that they are small with t' shapes similar to those of the incoherent events and without a peak at low t'. On the contrary, $K_{\pi 2}$ beam decays show a peak at small t' when fitted to the reaction $K^-\pi^0X$. A study of these false $K^-\pi^0X$ events shows that they have K^- backward in the K^* rest system, for $M_{K\pi}$ in the K^* mass region, and would thus create a forward-backward asymmetry if some were present in the data. No significant effect of this kind is observed. Thus, we conclude that the t' distribution of $K\pi X$ events in the $K^*(890)$ region cannot be explained simply as a sum of incoherent events and background events. We now show that the excess of events at low t' is compatible with coherent production of $K^*(890)$.

Interpretation of K^* events in the low-t' region.—On the basis of an optical model[2,7] of high-energy particle-nucleus interactions, the coherent differential cross section $d\sigma/dt')_A$ on a nucleus corresponding to the differential cross section $d\sigma/dt')_N$ for the same reaction on a nucleon is given by

$$\frac{d\sigma}{dt'}\bigg)_A = \frac{d\sigma}{dt'}\bigg)_N^\dagger F(t', \sigma_{K^*}, k_{\text{lab}}).$$

F is the nuclear form factor squared, σ_{K^*} the outgoing K^*-nucleon total cross section, and k_{lab} is the beam momentum in the lab system. $d\sigma/dt')_N^\dagger$ corresponds to that part of the amplitude on a nucleon which can lead to coherent production of K^*. We will assume that $d\sigma/dt')_N^\dagger$ is equal to $d\sigma/dt')_N$, since K^{*-} production on free protons at small t' by K^- beams in the 10-GeV/c momentum range can be understood[1] by ω and P' exchange alone, and since coherent production can occur via these exchanges.[2,8]

The t' dependence of F is roughly exponential in the low-t' region, with a slope Λ of about 100 $(\text{GeV}/c)^{-2}$ for nuclei of $A \approx 20$. The shape of $d\sigma/dt')_A$ can thus be taken as $\sim t'e^{-110t'}$, which means that we expect for $d\sigma/dt')_A$ a very sharp forward dip followed by a maximum at $t' \simeq 0.01$ $(\text{GeV}/c)^2$. Folding this distribution with our experimental resolution fills in the dip and reduces the slope considerably (Fig. 2 "coherent" curve).

Using these shapes for the coherent and incoherent distributions, we have fitted our events by a linear combination of the two distributions, the only free parameter being the relative abundance of coherent and incoherent events. As shown in Fig. 2 (solid curve) this method gives a good description of our data. The number of coherent events in the $K^*(890)$ region given by this fit is 42 ± 8. Thus, the coherent production in the K^* mass region appears as a 5-standard-deviation effect.

The $\cos\theta^*$ distribution (Fig. 3) for the low-t' events in the K^* region is consistent with the $\sin^2\theta^*$ shape expected for production by natural-parity exchange of a vector meson with helicity ± 1. (θ^* is the polar angle between the beam and the outgoing K evaluated in the $K\pi$ center-of-mass frame.) The associated azimuthal angle ψ^* (not shown) is badly determined for small t', and thus does not provide a further check of natural-parity exchange.

Cross sections.—For each energy we have calculated cross sections for the two channels ($K^-\pi^0$ and $\bar{K}^0\pi^-$) separately, using chamber detection and scanning efficiencies estimated for each decay mode. For this a subtraction is made of the background interpolated from the $K\pi$ mass plot into the $K^*(890)$ band. In the case of the $K^-\pi^0$ mode it is also possible to use the ratio of $K^-\pi^0$ events to $K_{\pi 2}$ beam decays, where most of the chamber efficiencies cancel approximately, to calculate cross sections at the two energies. The two procedures give compatible results for $K^-\pi^0$. The values obtained for the two channels are consistent with the ratio $\bar{K}^0\pi^-/K^-\pi^0 = \frac{2}{1}$ expected for decay of a K^* with $I = \frac{1}{2}$. Combining numbers for both channels, we find coherent cross sections for production of $K^{*-}(890) \to$ all $K\pi$ on $A \approx 20$ nuclei to be 131 ± 35 μb at 12.7 GeV/c and 150 ± 50 μb at 10 GeV/c.

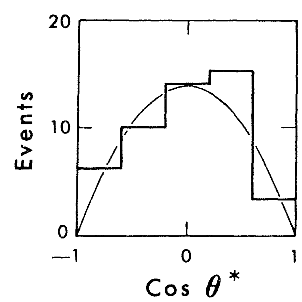

FIG. 3. Jackson angular distribution of $\hat{K}_{\text{in}} \cdot \hat{K}_{\text{out}}$ in $K\pi$ rest system, for 48 events with $t' < 0.07$ GeV/c^2 and $M_{K\pi}$ in K^* mass region. A $\sin^2\theta^*$ curve is drawn for comparison.

Using a calculated expression[2,7] for $F(t', \sigma_{K^*}, k_{lab})$ and the known shape of $d\sigma/dt')_N$, one can estimate from $\sigma_A{}^{K^*}$ the value of $\sigma_N{}^{K^*}$, where $\sigma_N{}^{K^*}$ is the integral of $d\sigma/dt')_N$ over t'. We have assumed here that the K^- and K^{*-} total cross sections on nucleons are equal. The ratio $\rho = \sigma_A{}^{K^*}/\sigma_N{}^{K^*}$ is quite sensitive to the shape of $d\sigma/dt')_N$ in the dip region where the uncertainties in the hydrogen data are rather large and not well indicated by the error on λ. With $\lambda = 10.8 \pm 0.5$ $(\mathrm{GeV}/c)^{-2}$, we find $\sigma_N{}^{K^*} = 107 \pm 30$ μb at 12.7 GeV/c and $\sigma_N{}^{K^*} = 146 \pm 50$ μb at 10 GeV/c. The latter value is in good agreement with the cross section for K^{*-} production from hydrogen[6] at 10 GeV/c.

Conclusion.—We have observed coherent production of $K^{*-}(890)$ by K^- beams on nuclei with $A \approx 20$. The observed effects are consistent with the hypothesis that $K^*(890)$ production on a nucleon is dominated by exchange of natural-parity, isoscalar trajectories.

We are grateful to the Brookhaven National Laboratory 80-in. bubble chamber personnel for their successful operation of the chamber with a Ne-H_2 mixture, and to the CERN 1.2-m heavy-liquid bubble chamber personnel. The encouragement and counsel of Professor A. Lagarrigue is much appreciated as well as information supplied by W. Kittel and D. R. O. Morrison. We thank W. R. Graves, J. F. Grivaz, and M. Novak for their contributions to various aspects of the experiment.

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[2]L. Stodolsky, Phys. Rev. 144, 1145 (1966); H. H. Bingham, CERN Report No. D. Ph. II/70-60, and in Proceedings of the Eleventh Cracow School of Theoretical Physics (to be published).

[3]I. Butterworth *et al.*, Phys. Rev. Lett. 15, 500 (1965); W. Hoogland *et al.*, Nucl. Phys. B11, 309 (1969); R. L. Eisner *et al.*, Phys. Lett. 28B, 356 (1970); D. Denegri *et al.*, Nucl. Phys. B28, 13 (1971).

[4]A. M. Cnops *et al.*, Phys. Rev. Lett. 25, 1132 (1970). See also B. Daugeras, thesis, Laboratoire de l'Accélérateur Linéaire, Orsay, France, Orsay Report No. LAL-1244, 1971 (unpublished); D. Fournier, Orsay Report No. LAL-1237, 1970, and thesis, Laboratoire de l'Accélérateur Linéaire, Orsay, France, Orsay Report No. LAL-1242, 1970 (unpublished).

[5]$t' = |t| - |t|_{\min}$, where t is the four-momentum transfer squared from target to recoil and $|t|_{\min}$ is the smallest kinematically allowed transfer to produce the $K\pi$ system.

[6]M. Aderholz *et al.*, Nucl. Phys. B5, 567 (1968). The cross section given in that paper has been superseded by the value $\sigma(K^-p \to K^{*-}p) = 140 \pm 9$ μb at 10 GeV/c: D. R. O. Morrison, private communication.

[7]Fournier, Ref. 4.

[8]We assume that the contribution from γ exchange is small for $A \approx 20$ and $P_{\mathrm{beam}} \lesssim 13$ GeV. This assumption is based on an optical-model calculation using the SU(3) prediction that the partial width of $K^* \to K\gamma$ is ≈ 62 keV. See also F. R. Huson *et al.*, Phys. Lett. 20, 91 (1966).

Angular-Momentum Cuts and Scaling of Total Cross Sections at High Energies*

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High-energy total cross sections for the $\pi^\pm p$, $K^\pm p$, $\bar{p}p$, and pp reactions are analyzed using a Regge-pole model combined with an odd-signature cut. It is found that the asymptotic cross sections, when plotted versus $\omega = s/2M_1M_2$, satisfy a scaling law within specified normalization constants.

About nine years ago[1] one of us proposed a phenomenological model of high-energy forward elastic scattering, dominated by a Pomeranchukon pole plus cut; and the high-energy data for πp, Kp, $\bar{p}p$, and pp scattering were analyzed in a series of papers.[2] The model was mainly motivated by the multiperipheral field theory of Amati, Fubini, and Stanghellini.[3] In the intervening years, a plethora of literature on Regge cuts has appeared,[4] but our fundamental understanding of these cuts has not increased significantly; a bewildering number of dips and polarization effects have been discovered in hadronic reactions, and the appealing simplicity of the initial Regge-pole picture has been irretrievably lost.

However, an aspect of the angular-momentum cuts that was already recognized in Ref. 2, which perhaps goes beyond a mere attempt to guess the