Table I. Effects of radial cut-offs on the failure of reciprocity.

Cut-off radius (fm)	Average $\|\mathfrak{R}\|$ (%)
0	6.04
4.1	1.96
6.1	0.13
8.1	0.006

The average value of $|\mathfrak{R}|$ is 0.63% with this normalization. For a T-odd potential of $\frac{1}{2}$ the range shown in the figure, the result is very similar, with an average value of $|\mathfrak{R}|=0.51\%$. In Fig. 2(b) we plot the ratio $\mathfrak{R}$ when the violation of reciprocity arises from V_n. The curves are for radii of a Woods-Saxon potential of 4.1 fm (the nuclear radius for the T-even part) and 1.0 fm. As anticipated from Robson's work, the violation is appreciably reduced in the latter case. No particular correlation of the violation $\mathfrak{R}$ with the angular distribution is observed. The average values of $|\mathfrak{R}|$ are 6.0 and 0.41% for ranges of 4.1 and 1.0 fm, respectively. For the first of these cases we have cut off the radial integrals at various radii and find that the deviation of $|\mathfrak{R}|$ from zero decreases as shown in Table I. The case of 1.0 fm is an artificial one for the potential which binds the neutron to the core, but shows the effect of a small range. Reciprocity is much less sensitive to the range of the n-p potential, V_{np}. Furthermore, the ranges of the forces that violate time-reversal invariance need not be much less than that which arises from one-pion exchange if the model suggested by Bernstein, Feinberg, and Lee[8] is assumed. We are presently calculating this force.

In conclusion, we note that direct reactions are sensitive to T-odd terms that may be present in the nuclear Hamiltonian. The violation of reciprocity, as defined by Eq. (3), is roughly equal to the ratio of the T-odd force to the normal one.

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†J. S. Guggenheim fellow, 1967-1968.

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COHERENT PRODUCTION OF THE Q AND L MESONS OFF DEUTERIUM*

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Abundant production of the established L meson and also of the possible Q meson are observed in coherent production, $K^-d \rightarrow K^-\pi^+\pi^-d$, at 12.6 BeV/$c$. This is the first observation of L-meson production on nuclei. The Q and L isospins are unambiguously determined to be $\frac{1}{2}$. The L is observed to be produced polarized. A striking resemblance between the final states $K^*(890)\pi d$ and $K^*(1400)\pi d$ is observed with these final states being related to the Q and L mesons, respectively.

In this Letter we present evidence for the production of the $Q(1300)$ and the $L(1700)$ resonances[1-3] decaying into $K^-\pi^+\pi^-$, and being formed coherently in K^- interactions on deuterium. As the deuteron has isospin 0, these are determined to be isospin-$\frac{1}{2}$ states. We have investigated the spin-parity properties of these states. Some aspects of our data have already been presented.[4]

The film was obtained in an exposure of the Brookhaven National Laboratory 80-in. bubble chamber, filled with deuterium. The rf-separated beam[5] was used to obtain K^- particles at a momentum of 12.6 BeV/c. The 100 000 pictures taken have been scanned once, and $\frac{2}{3}$ of the available data have been measured.

We have selected for measurement all four-prong events which satisfied fiducial volume requirements and had one heavily ionizing track shorter than 15 cm. These were kinematically fitted to the final states

$$K^-d \to K^-\pi^+\pi^-d, \tag{1}$$

$$K^-d \to K^-\pi^+\pi^-np. \tag{2}$$

Although almost all fits to Reaction (1) also fit (2), we have found that using all events which fit (1) leads to a nondeuteron-event contamination of less than 5%.[4] For an acceptable $K^-\pi^+\pi^-d$ event we have required that the χ^2 probability in the fit to (1) be greater than 1% and that the cosine of the angle between the n and p directions in the fit to (2) be greater than 0.5. In 97 of our 240 accepted events we cannot determine which negative particle is the K^-. When possible we have selected that fit which had a $K^-\pi^+$ mass within 50 MeV of the $K^*(890)$.[4] The 51 events which had a $K^*(890)$ in both or neither fit are considered "unresolvable" and are plotted, as shaded events, once for each fit with half weight.

In Fig. 1(a) we present the momentum transfer distribution to the d system for all accepted fits to Reaction (1). The curve is

$$A \exp(7t)|F(t)/F(0)|^2,$$

where $F(t)$ is the deuteron form factor[6] and the distribution is normalized to the events with $-t$ between 0.04 and 0.20 (BeV/c)^2. This distribution is not affected by the $K^-\pi^-$ ambiguity problem so that no events are shaded. In Reaction (2) the t distribution is $A\exp(\lambda t)$ with $\lambda = 7$ (BeV/c)$^{-2}$.

In Fig. 1(b) the effective-mass distribution of the $K^-\pi^+\pi^-$ system is shown with the resolvable events in white and the unresolvable ones hatched. There are two broad peaks, one in an interval of 1100 to 1400 MeV and the second from 1600 to 1800 MeV.[7] We shall refer to these as the Q and L without trying to resolve them into finer peaks.[8] In Figs. 1(c) and 1(d) are shown the $K^-\pi^+\pi^-$ mass distributions for $K^*(1400)$ and $K^*(890)$ events.[9] The Q is seen to be associated mainly with $K^*(890)\pi$ and the L peak is due mainly to the $K^*(1400)\pi$ contribution. We have looked for similar effects in the final states $\bar{K}^0\pi^-d$ and $\bar{K}^0\pi^-\pi^+\pi^-d$ but have only seven and four candidates for these channels, respectively. There are at most four $K^*(890)$ and one $K^*(1400)$ events in $\bar{K}^0\pi^-d$ making the sequence $1^-, 2^+$ suppressed at our energies. The three- and five-body coherent production channels, corrected for K_1^0 decay detection and an estimate of scanning efficiency, contain not more than 30 and 18 events as compared with 250 in the four-body final state. Similar results, with two-pion and four-pion versus three-pion final states, have been observed in coherent pion-nucleus scattering.[10] This is consistent with a model in which high-energy peripheral processes are dominated by 0^+ or "Pomeranchukon" exchange.[11] There are no $K^0\pi^-d$ events with the $K^0\pi^-$ mass in the Q and only one in the L re-

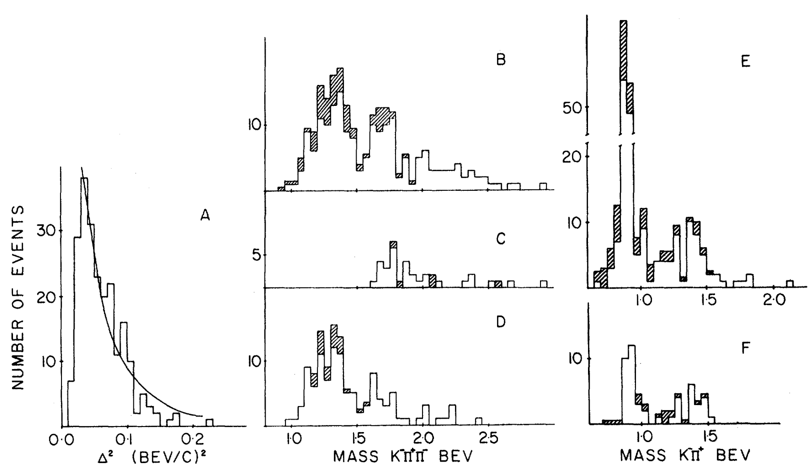

FIG. 1. (a) Momentum transfer distribution to the d in Reaction (1). (b) $K^-\pi^+\pi^-$ mass distribution for all events. (c) $K^-\pi^+\pi^-$ mass distribution for $K^*(1400)$ events. (d) $K^-\pi^+\pi^-$ mass distribution for $K^*(890)$ events. (e) $K^-\pi^+$ mass distribution. (f) $K^-\pi^+$ mass distribution for events in the L region.

gion, making it plausible that these states are in the sequence $0^-, 1^+, 2^-, 3^+, \cdots$.

In Fig. 1(e) we show the $K^-\pi^+$ mass distribution for all events and see the large signal of $K^*(890)$ and a prominent $K^*(1400)$ bump. We do not see a statistically significant amount of $K^-\rho^0 d$. We have made a cut on the $K^-\pi^+\pi^-$ mass in the L region as defined above and plotted the $K^-\pi^+$ mass distribution in Fig. 1(f). The L is seen to contain comparable amounts of $K^*(890)\pi$ and $K^*(1400)\pi$, but our evidence that the $K^*(890)\pi$ system peaks in this region is weak. The $K^*(1400)\pi$ signal is like a Deck-type threshold effect[12] although we have not examined this possibility in detail.

The remainder of this Letter will be devoted to a discussion of the angular distributions in the Q and L regions. From a theoretical viewpoint these distributions should reflect the fact that the Q and L spin substates $m=0$ relative to the beam direction are believed to be preferred in high-energy peripheral collisions. This is true both in the Regge-pole model[13] and the diffraction dissociation model (for the sequence $J^p = 0^-, 1^+, 2^-, \cdots$).[12] The Regge-pole model predicts, for incident 0^-, that the sequence $0^+, 1^-, 2^+, 3^-$ is suppressed at high energies as does the diffraction dissociation model, to the extent that diffraction dissociation is the principal mechanism for high-energy quasielastic peripheral collisions. Since our experiment is at a "high" energy and the collisions are extremely peripheral due to the deuteron form factor, we expect that the above conditions will apply.

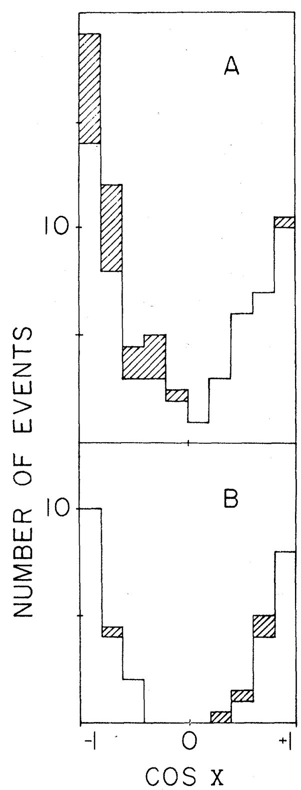

FIG. 2. (a) Cosχ distribution for the decay of the $K^*(890)$ in $K^*(890)\pi d$ events with $K^*\pi$ in the Q region. (b) Cosχ distribution for the decay of the $K^*(1400)$ in all $K^*(1400)\pi d$ events.

Four angular distributions are plotted in Figs. 2 and 3, and will be defined here. The events in Fig. 2 have mass cuts on the $K^*(890)$ and $K^*(1400)$[9] while the others have cuts on the Q and the L regions. χ is the angle between the outgoing π^+ and the incident K^- as observed in the $K^*(890)$ c.m. system for Q events and in the $K^*(1400)$ c.m. system for all $K^*(1400)$ events. θ and φ are the polar and azimuthal angles of the normal to the $K^-\pi^+\pi^-$ decay plane (K^- cross π^+) in the $K^-\pi^+\pi^-$ c.m. system which has the z axis in the direction of the K^- beam particle and the y axis in the direction of the normal to the production plane (beam cross incident deuteron). The angle ψ is the angle between the normal to the decay plane and the normal to the production plane.

As has been observed before, the alignment of the $K^*(890)$ relative to the beam direction for events in the Q region [as displayed in Fig. 2(a)] suggests that the Q is a 1^+ s-wave $K^*\pi$ resonance produced with $M_Q = 0$ in the c.m. system described above.[2] Also, the alignment of the $K^*(1400)$, as displayed in Fig. 2(b), suggests that the L region contains a 2^- s-wave $K^*(1400)\pi$ res-

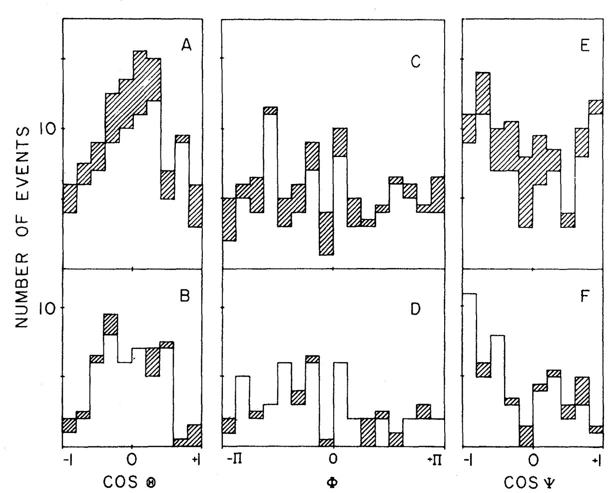

FIG. 3. (a) Cosθ distribution for Q events and (b) for L events. (c) φ distribution for Q events and (d) for L events. (e) Cosψ distribution for Q events and (f) for L events.

onance which is produced with $M_L = 0$.[4] The emission of the $K^*(890)$ and the $K^*(1400)$, from the Q and the L, respectively, are isotropic, supporting the s-wave condition. We proceed to test these conjectures by examining the other angular distributions.

In the case of the Q, with the 1^+ assumption, it is predicted that[14] (i) the $\cos\theta$ distribution be $\sin^2\theta$, (ii) the φ_n distribution be flat, and (iii) the distribution in $\cos\psi$ be $1+\cos^2\psi$. As can be seen from Figs. 3(a), 3(c), and 3(e), these predictions are fitted quite well.

If the L is a 2^- system made with $M_L = 0$, we expect (i) the $\cos\theta$ distribution to be $(15/8)\sin^4\theta + K(5\cos^4\theta - 2\cos\theta - \frac{1}{3})$, (ii) the φ distribution to be flat, and (iii) the ψ distribution to be an even function of ψ depending on the same positive parameter K. In Figs. 3(b), 3(d), and 3(f), these distributions are displayed. A definite $\sin^4\theta$ dependence can be seen in the $\cos\theta$ distribution. However, a $\sin\varphi$ and $\cos\psi$ dependence are also evident and do not fit the above model. The up-down asymmetry in $\cos\psi$ cannot occur, for a pure resonance, without the exchange of spin in the L channel. Our evidence for the asymmetry is that there are 18 events in the two leftmost bins as opposed to 4 in the two rightmost. This asymmetry is incompatible with the L being a 0^- or 1^- state but is compatible with 1^+, 2^+, or 2^-. Assuming that the dominant effect in the L region is a $J^P = 2^-$ state, two possibilities are evident: (a) The L is the major contributor and is made by exchange of spin in the t channel, or (b) the L is made by 0^+ exchange, but there is another resonance or background interfering strongly with it.

There have been reported two resonances in the L region at 1660[15] and 1790 MeV,[3] although these are somewhat far apart.

We have also looked at the final state $K^-\pi^+\pi^-np$ and find that (i) the L region is not significantly enhanced, and (ii) the asymmetry in $\cos\psi$ in the L region is not present for these deuteron breakup events.

In conclusion we summarize our findings and make some speculations about the L region. (i) We find an isospin-$\frac{1}{2}$ $K\pi\pi$ system which has all the characteristics of a 1^+, s-wave, $K^{*0}\pi^-$ resonance (the Q) made by the exchange of a 0^+ particle. (ii) We find an isospin-$\frac{1}{2}$ enhancement from 1600 to 1800 MeV in $K\pi\pi$ mass which shows some characteristics to be associated with a $J^P = 2^-$ system, i.e., $K^*(1400)$ alignment and the $\cos\theta$ distributions.[16] (iii) Spin effects are important in the t channel for the L-mass region in the process we are studying. We are investigating the possibility that the L region is due to two resonances interfering to give the $\cos\psi$ dependence. We note that the Regge recurrences of both the K^- and $K^{*-}(890)$ are expected to be somewhere in the L region.

We thank Dr. H. Foelsche and his assisting staff for help with the rf separated beam and Dr. R. Shutt and the 80-in. bubble chamber crew for their efforts in obtaining this deuterium exposure. We have had many helpful discussions with Dr. G. Feldman, Dr. T. Fulton, Dr. D. Griffiths, Dr. G. Kane, and Dr. L. Madansky. Most of the computation was done at the New York University Computing Center. Finally, we acknowledge the efforts of our scanners and measurers who have made this work possible.

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SPECTRUM OF NEUTRONS FROM MUON CAPTURE IN SILICON, SULFUR, AND CALCIUM*

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The energy spectrum of neutrons emitted following the capture of negative muons in silicon, sulfur, and calcium has been measured between 7.7 and 52.5 MeV. The spectra were found to decrease exponentially with energy in the three cases, and no evidence was found for excitation of giant dipole resonances.

The neutron-energy spectrum can be represented as the sum of the evaporation spectrum,[1] the giant-resonance spectrum,[2] and the direct spectrum.[3,4] A measurement of the total spectrum provides information concerning the contribution of each component, since the shapes of the three contributing spectra differ. In addition, the shape of each of these components depends on the nuclear model used, so that the validity of various models can be tested. The expected asymmetry of the neutrons is a function of the mechanism by which they are produced and of their energy; so a measurement of the energy spectrum of the neutrons is important for the interpretation of the measured asymmetry.

Experiment.—This experiment[5] was performed using the negative beam from the muon channel of the Carnegie-Mellon University synchrocyclotron. The following paper discusses the data on neutron asymmetries, which were studied at the same time. Negative muons were stopped in the target, as shown in Fig. 1. Neutrons emitted following muon capture by a target nucleus were detected in counter 5.

The time between the stopping of a muon and the detection of an event in counter 5 was measured by a 100-MHz digital timing system. This time and the pulse height in counter 5 were simultaneously measured, and this two-dimensional information was stored in a 1600-channel pulse-height analyzer. The time measurement permits the accurate subtraction of background events. The neutron-energy spectrum was determined by unfolding the observed pulse-height spectrum.

Target stops were defined by $1234\overline{69}$. Stops in counter 4 were rejected by a technique employing the pulse heights in counters 3 and 4.[6]

Counter 5 comprised a volume of NE-213 liquid scintillator viewed by a 58AVP photomultiplier. Pulse-shape discrimination was used to distinguish gammas from neutrons. A neutron event was defined by $5\overline{69}$ in coincidence with a pulse-shape discriminator (PSD) pulse. A decay-