the work of Lee,[6] who has studied an operator formulation[7] of the droplet model in which the eikonal is replaced by an operator source function. He finds that this source function must be the density of a conserved charge in order to have finite differential cross section at infinite energies.

This remark originated in an unpublished investigation of the propagation of neutral K mesons through matter. It is a pleasure to acknowledge several discussions with Professor L. Foldy and Professor C. N. Yang.

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OBSERVATION OF A FOUR-PION RESONANCE AT 1630 MeV in K^+p INTERACTIONS AT 10 GeV/c†

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We report the observation of a new four-pion resonance $\rho(1630)$ with mass 1632 ± 23 MeV and width 110^{+40}_{-30} MeV produced in the channel $K^+p \to K^0\pi^+\pi^+\pi^-\pi^0p$ and decaying predominantly to $\rho^{0,-}\pi^{0,+}\pi^+$ and $\omega\pi^+$. No decay is observed into $\pi^+\pi^0$, $K^+\bar{K}^0$, $\rho^+\rho^0$, or $A_2\pi$, so that association with the g is precluded and the spin and parity probably lie in the unnatural series. The $\rho(1630)$ is associated with a $K\rho(1630)$ enhancement near threshold. This and other production characteristics are consistent with a double Regge pole exchange mechanism.

The four-pion decay mode of a boson resonance in the 1700-MeV region was first observed by Bellini et al.[1] Confirmation has come from several other πp production experiments[2-7] and $\bar{p}p$ annihilation experiments.[8,9] Evidence for decays via $\omega\pi$,[3,5,7] $A_2\pi$,[2,4,8] and $\rho\rho$[3-5] has also been claimed. The evidence points to the existence of a resonance[10] $\rho(1710)$ decaying predominantly to four pions but in individual experiments[5] this mode has been difficult to disentangle from possible four-pion decay modes of the $g(1660)$. The CERN Missing Mass Spectrometer Group (MMS)[11] observe several enhancements in this mass region which are appreciably narrower than those claimed in bubble chamber experiments. We report here the observation of a new resonance $\rho(1630)$ produced in the reaction

$$K^+p \to K^0\rho(1630)^+p \qquad (1)$$

at 10 GeV/c incident momentum and decaying predominantly to $\rho^{0,-}\pi^{0,+}\pi^+$ and $\omega\pi^+$, but with no detectable $\pi^0\pi^+$, $\rho^0\rho^+$, $A_2^{0,+}\pi^{+,0}$, or $\bar{K}^0K^+$ decay modes.

Experimental details. – A double scan was made of 500 000 pictures of the 2-m CERN hydrogen bubble chamber exposed to a 10-GeV/c separated K^+-meson beam for the topologies two-prong + V^0 and four-prong + V^0. After measurement, kinematic analysis and ionization checks, the yields of uniquely identified events are as follows[12]:

$$K^+p \to K^0\pi^+\pi^+\pi^-\pi^0p, \quad 2984 \text{ events}; \qquad (2)$$

$$K^+p \to K^0\pi^+\pi^0p, \quad 4463 \text{ events}; \qquad (3)$$

and

$$K^+p \to K^0K^+\bar{K}^0p, \quad 720 \text{ events.} \qquad (4)$$

Four-constraint production fits and K^0-meson decay fits were required to have probability above 1%. Only those one-constraint production fits with probability greater than 5% and not ambiguous with any four-constraint fit were accepted. Fits to Reaction (2) ambiguous with other one-constraint fits or internally ambiguous were also excluded; these fits involve predominantly the high $(4\pi)^+$ mass region and their treatment is not pertinent to our conclusions.

Mass distribution. – Figure 1(a) shows the total $(4\pi)^+$ effective-mass distribution for Reaction (2). The cross-hatched histogram shows the effect of selecting only events where the effective mass of any $\pi^+\pi^-$ or $\pi^0\pi^-$ combination lies in the $\rho(760)$ region (640 to 820 MeV) or where the effective mass of any $\pi^+\pi^-\pi^0$ combination lies in the $\omega(780)$ region (750 to 810 MeV). There is a clear enhancement between 1560 and 1700 MeV. The corresponding mass plots for the $(\pi^+\pi^0)$ combinations from Reaction (3) and for the K^+K^0 or $K^+\bar{K}^0$ combinations from Reaction (4) appear in Figs. 1(b) and 1(c), respectively. Using the signal and guard bands shown in Fig. 1 the excess of events in the $\pi^+\pi^0$ spectrum between 1560 and 1700 MeV is -12 ± 18, and for the $K^+\bar{K}^0$ spectrum it is -15 ± 10. These numbers compare with 75 ± 18 events for the $(4\pi)^+$ mass distribution. Some comparison plots for events in the same signal band, 1560 to 1700 MeV in $(4\pi)^+$ mass, and the same guard bands, 1490 to 1560 MeV and 1700 to 1770 MeV, are shown in Fig. 2. The outline histograms refer to the events in the signal region and the cross-hatched histograms show the effect of guard-band subtraction. The $\pi^+\pi^-$, $\pi^-\pi^0$, and $\pi^+\pi^-\pi^0$ effective-mass plots in Figs. 2(a), 2(b), and 2(d), respectively, show evidence of strong ρ^- and ρ^0 production with some ω^0 production. Figures 2(a) and 2(b) suggest there is strong ρ^0,ρ^- overlap and this is confirmed by examination of correlation plots. The $\pi^+\pi^0$ effective-mass plot [Fig. 2(c)] closely resembles the $\pi^+\pi^+$ effective-mass plot (not shown). The curves in Figs. 2(c) and 2(d) are calculated assuming a decay $\rho(1630)\to\rho(760)\pi\pi$, where both resonances are assumed

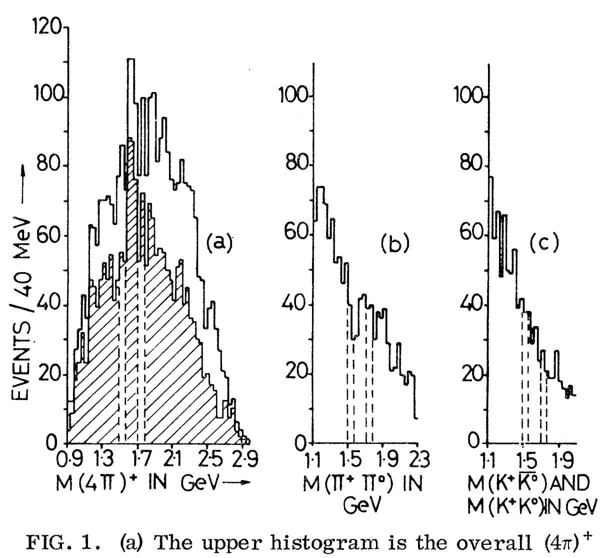

FIG. 1. (a) The upper histogram is the overall $(4\pi)^+$ effective-mass plot for Reaction (2) and the cross-hatched histogram shows the effect of ρ^0 or ρ^- or ω^0 selection. Signal band and guard bands are indicated by broken lines. (b) Overall $(\pi^+\pi^0)$ effective-mass plot for Reaction (3). (c) Overall $\bar{K}^0K^+$ plus K^0K^+ effective-mass plot for Reaction (4).

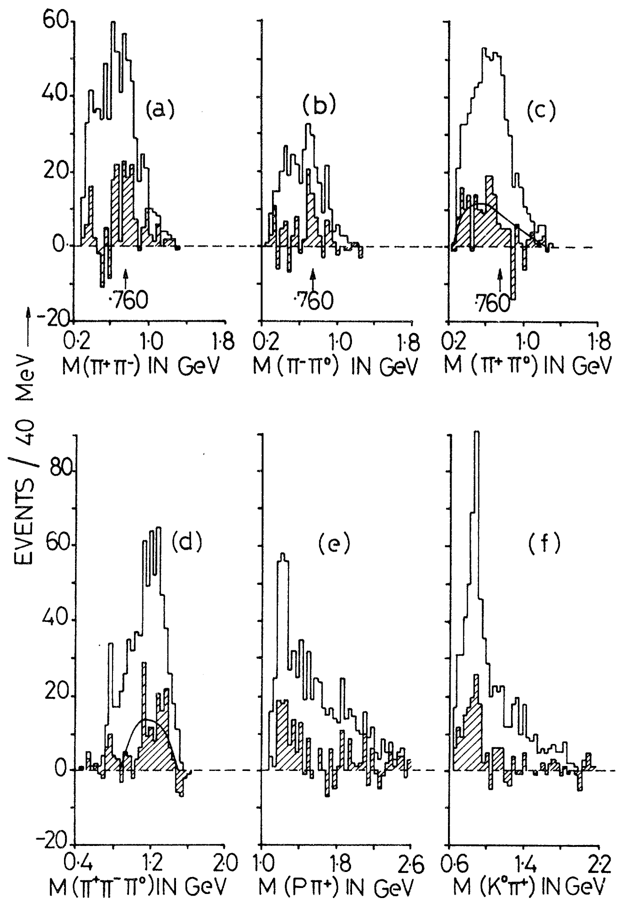

FIG. 2. Comparison plots of effective masses for the signal region of Reaction (2) before (outline) and after (cross-hatched) guard-band subtraction: (a) for $\pi^+\pi^-$; (b) for $\pi^-\pi^0$; (c) for $\pi^+\pi^0$; (d) for $\pi^+\pi^-\pi^0$; (e) for $p\pi^+$; and (f) for $K^0\pi^+$ combinations. The curves are discussed in the text.

to decay isotropically in their rest frames; for the two-pion spectrum a pion from the $\rho(760)$ and an external pion were paired. We conclude that the signal is associated with $\rho^{-,0}\pi^{+,0}\pi^+$ and $\omega\pi^+$, but not with A_2 or ρ^+ and hence not with $\rho^+\rho^0$. Reaction (2) shows strong $\Delta(1236)$ and $K^*(890)$ production which could enhance ρ^- or ρ^0 production. Figures 2(e) and 2(f) indeed reveal that a considerable fraction of the signal could be associated with $p\pi^+$ ($K^0\pi^+$) combinations having effective masses in the Δ^{++} (K^{*+}) region. We have, therefore, calculated the $(4\pi)^+$ mass spectrum for the reaction $K^+p \to K^{*+}\rho^-(760)\Delta^{++}$ using the Chan, Loskiewicz, and Allison (CLA)[13] model assuming meson exchange only and isotropic K^{*+} and Δ^{++} decays in their rest frames. The predicted spectrum shows that no enhancement is obtained in the signal region. We have also examined the angular distributions of the π^+ mesons from $p\pi^+$ ($K^0\pi^+$) combinations with effective masses between 1180 and 1340 MeV (840 and 940 MeV). In the signal region we find backward peaking of the π^+ direction in the $p\pi^+$ ($K^0\pi^+$) rest frame with respect to the $p\pi^+$ ($K^0\pi^+$) line of flight while in the guard bands this distribution is more symmetric. These features support the conclusion that the overlaps with the $K^*(890)$ and $\Delta(1236)$ regions are kinematic in origin. Thus we are observing a genuine $(4\pi)^+$ resonance with isospin 1.

Selecting only those events having a ρ^- or ρ^0 (640 to 820 MeV) but no ω^0 (750 to 810 MeV) gives the $(4\pi)^+$ mass plot of Fig. 3(a); Fig. 3(b) is the corresponding ω^0-selected plot and the hatched histogram in Fig. 3(a) the ρ^--selected plot.[14] The latter shows the clearest signal because there is only one $\pi^-\pi^0$ combination per event. Fits to Figs. 3(a) and 3(b) give $M(\rho\pi\pi) = 1627^{+12}_{-17}$, $\Gamma(\rho\pi\pi) = 72^{+29}_{-20}$, and $M(\omega\pi) = 1654 \pm 24$, $\Gamma(\omega\pi) = 130^{+73}_{-43}$. The backgrounds are so dissimilar for $\rho\pi\pi$ and $\omega\pi$ that we have combined these two independent values directly to give $M = 1632 \pm 20$ and $\Gamma = 93^{+40}_{-25}$; so we shall refer to this resonance as the $\rho(1630)$. The observation of very narrow peaks in the CERN MMS experiment has prompted us to replot the overall $(4\pi)^+$ mass spectrum in 20-MeV bins as Fig. 3(e). Within the limited statistics the data are certainly consistent with two narrow peaks near 1630 MeV.

Spin and Parity.—The absence of any detectable $\pi^+\pi^0$ decay mode establishes clearly that the $\rho(1630)$ is different from the $g(1660)$. We claim that the $\rho(1630)$ is a new resonance decaying predominantly to $\rho^{0,-}\pi^{0,+}\pi^+$ and $\omega\pi^+$. It differs from the $\rho(1710)$ because of the mass separation and

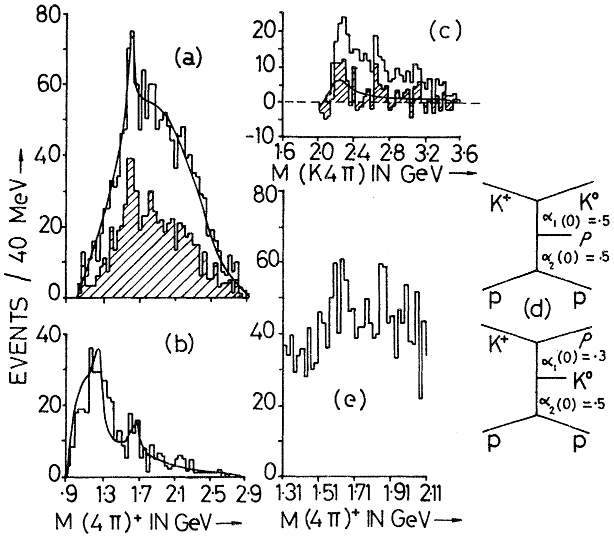

FIG. 3. (a) The upper histogram is the $(4\pi)^+$ effective-mass plot for Reaction (2) with ρ^0 or ρ^- selection and ω^0 antiselection and the hatched histogram is for ρ^- selection only. The ρ region was taken from 640 to 820 MeV and the ω^0 region from 750 to 810 MeV. (b) As (a) but with ω^0 selection only. The fits to (a) and (b) are discussed in the text. (c) The $K^0 4\pi$ effective-mass plot for Reaction (2) for the $(4\pi)^+$ signal region, before (outline) and after guard-band subtraction (cross-hatched). The fitted curve is obtained using the model of Chan, Loskiewicz, and Allison (Ref. 13) with the diagrams shown in (d). (e) The overall $(4\pi)^+$ effective-mass plot for Reaction (2) replotted in 20-MeV bins.

the absence here of detectable $A_2\pi$ or $\rho\rho$ decay modes. The strength of the ρ^- signal and the absence of any ρ^+ signal in our data are particularly intriguing features and require that the $\rho(\pi\pi)_{I=2}$ decay mode is large compared to any $\rho(\pi\pi)_{I=0,1}$ modes. On the basis of the presence or absence of various decay modes certain spin and parity assignments for the $\rho(1630)$ can be excluded with varying degrees of certainty: (1) The absence of the $\pi^+\pi^0$ mode rules out $1^-, 3^-, \cdots$; (2) the absence of the $K^+\bar{K}^0$ mode rules out $0^+, 2^+, \cdots$; (3) the $\omega\pi^+$ mode rules out 0^+. The preferred spin and parity choices are $0^-, 1^+, 2^-, 3^+, \cdots$. The absence of the $\rho^0\rho^+$ suggests that $0^-, 1^-, 2^-, \cdots$ are ruled out, but the low-energy release could suppress this mode. The observed distribution of the cosine of the angle (θ) which the ω decay-plane normal makes with the ω direction in the overall $(4\pi)^+$ rest frame peaks near $\cos\theta = \pm 1$. This is consistent with unnatural spin and parity assignment. We have also examined the decay angular distributions of the $\rho\pi\pi$ mode but find these are quite isotropic; hence we cannot draw any strong conclusions about the spin from them.

Production characteristics.—Finally we discuss the production mechanism for the $\rho(1630)$. Figure 3(c) shows the effective-mass plot of the $K(4\pi)^+$ system for the signal band before and after guard-band subtraction. There is an accumulation of events near threshold for the signal band only. We have fitted this and other related plots with a CLA model for Reaction (1) using the double peripheral diagrams also shown in Fig. 3(d) and the constants of Ref. 13. Possible exchange trajectories for the intercept of 0.5 are ρ, ω, A, and trajectories for the intercept of 0.3 are K^* and K^{**}. The one-dimensional distributions are fitted reasonably well and suggest that the threshold enhancement could be a kinematic effect, although the possibility that it could be a resonance is not ruled out.

We would like to thank the CERN proton synchrotron staff and the 2-m chamber crew for their help in obtaining the pictures. We are greatly indebted to Dr. P. Lazeyras and his colleagues who were responsible for the U5 beam. Thanks are also due to the Oxford University Film Analysis Group for their work on the earlier parts of the experiment. Lastly, we are grateful to the Science Research Council of Great Britain for their generous support.

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[12]The corresponding cross section after corrections for scanning losses, invisible decays, etc., are 817 ± 110, 1090 ± 115 μb for Reactions (2) and (3), and 62 ± 8 μb for Reaction (4) uncorrected for invisible decays.

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[14]Figure 3(a) was fitted with a smooth hand-drawn background and Breit-Wigner resonance. The background to Fig. 3(b) was calculated for the process $K^+p \to K^0\omega\pi^+p$ using the model of Ref. 13. This background peaks near 1100 MeV and it was necessary to include both the B meson and $\rho(1630)$ to obtain a good overall fit.

LIMIT ON THE $K^+ \to \pi^+ + \nu + \bar{\nu}$ DECAY RATE*

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The branching ratio for the process $K^+ \to \pi^+ + \nu + \bar{\nu}$ is shown by a counter spark chamber experiment to be less than 1.2×10^{-6} of all decay modes, assuming a pion energy spectrum like that of $K^+ \to \pi^0 + e^+ + \nu$. Our apparatus was sensitive to pions in the kinetic energy range 117-127 MeV.

In 1964 Camerini, Cline, Fry, and Powell[1] reported the results of a search for the reaction $K^+ \to \pi^+ + e^+ + e^-$. They set an upper limit of 2.5 $\times 10^{-6}$ on the branching ratio for this decay mode. Other experiments[2] have been made to search for $K_L{}^0 \to e^+ + e^-$, $K_{L,S}{}^0 \to \mu^+ + \mu^-$, and $K^+ \to \pi^+\mu^+\mu^-$. These decays have not been observed. In the experiment described here, we have searched for the decay

$$K \to \pi^+ + \nu + \bar{\nu}. \qquad (1)$$

We have observed no examples of this decay. If