Further calculation shows that the variation at the 30° peak arises primarily from the difference in energy of the outgoing particles.

The ratio of the integrated cross sections (11-90° c.m.) for these transitions, after correcting for the phase-space and isospin coupling factors, is $\sigma(p,t)/\sigma(p,{}^3\text{He}) = 0.905\text{ mb}/0.807\text{ mb} = 1.12/1$. This excellent agreement between the absolute cross sections, and the angular distributions, implies a strongly charge-independent interaction operator. Further, the analog states of ^{14}O and ^{14}N must be extremely similar. In addition to the principal $[(p_{1/2})^2]0^+$, $T=1$ component in these states, there can be admixtures of 0^+ states of $T \neq 1$ and admixtures of other 0^+, $T=1$ states. Since these amplitudes enter linearly into the matrix elements, though appropriately weighted by transition-dependent factors, the matrix-element ratio is a sensitive measure of differing amplitude and phase admixtures in the analog states.

Exact comparison of the ^{14}O(g.s.) and ^{14*}N (2.31 MeV) wave functions must await an accurate calculation of the effect of the different energies and Coulomb scattering in the exit channels on the relative cross sections. For example, however, let us assume that the ratio of the matrix elements depends solely upon differences in the wave functions of the analog states of ^{14}O and ^{14}N. Also, we will assume that this difference arises only from a unique $T=0$ impurity in the ^{14*}N(2.31 MeV) state[6] of 2×10^{-3} with a single amplitude and phase of -0.045. The predicted ratio of $\sigma(p,t)/\sigma(p,{}^3\text{He})$ would then be 1.10/1, which is comparable to the experimental ratio, even though the admixture is quite small.

We are indebted to Dr. Norman K. Glendenning for many valuable discussions.

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ANALYSIS OF THE 1.0- TO 1.4-BeV π-ρ ENHANCEMENT*

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Peripheral interactions of 8- to 16-BeV/c π mesons in heavy-liquid bubble chambers have been studied by Bellini et al.[1] and Huson and Fretter.[2] Both groups observed significant enhancements in the $\pi^-\pi^+\pi^-$ effective-mass distributions in the 1.0- to 1.4-BeV region; however, it was not possible to determine whether the effect resulted from the production of a new resonant state or from kinematics of diffraction dissociation. Recently, in a thorough analysis of the reaction $\pi^+ + p \rightarrow \pi^+ + \pi^+ + \pi^- + p$ at 3.65 BeV/c, Goldhaber et al. showed that most events could be classified into two distinct groups, $\rho^0 N^{*++}(1238)$ and $\rho^0\pi^+p$.[3] They observed the 1.0- to 1.4-BeV enhancement only in the $\rho^0\pi^+p$ events. We have studied this strong π-ρ interaction in $\pi^- + p \rightarrow \pi^+ + \pi^- + \pi^- + p$ and find that the enhancement consists of two clearly resolved peaks. In addition, decay of the higher mass system into $K\bar{K}$ is observed in the $K\bar{K}N$ final states. Possible spin and parity assignments for the two states are discussed.

The film was obtained in the course of a systematic study of 1.5- to 4.2-BeV/c π^-p interactions in the Lawrence Radiation Laboratory's 72-in. hydrogen bubble chamber. Approximately 30 000 pictures at 3.22 BeV/c with an average of 10 pions each were scanned for interactions leading to four charged secondaries; 7500 events were measured and processed. Where possible, ambiguities were removed by comparison of track ionization on the film with that calculated from the kinematic fits. For the remainder of the events, the fit with the highest confidence level

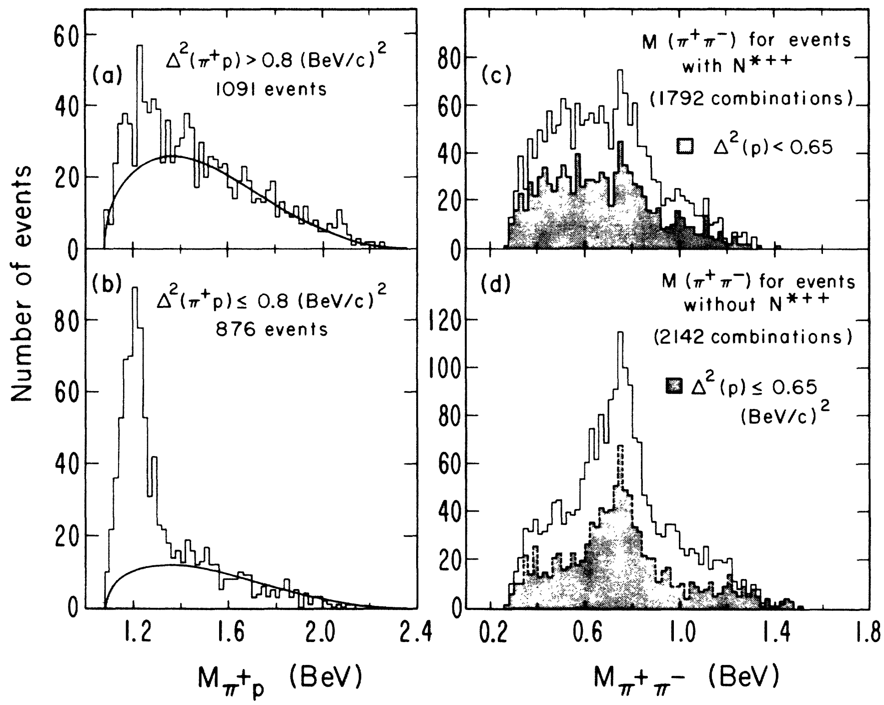

FIG. 1. Effective-mass distributions for (a, b) π^+p combinations at high and low momentum transfer; (c, d) $\pi^+\pi^-$ combinations with and without N^{*++}.

was used. In the present Letter, we discuss only the 1967 events fitting $\pi^- + p \rightarrow \pi^+ + \pi^- + \pi^- + p$. Since this final state represents the only four-constraint fit, these events constitute a particularly pure sample.

The π^+p effective masses, $M(\pi^+p)$, are plotted in Figs. 1(a) and 1(b). At low momentum transfer to the π^+p system, $\Delta^2(\pi^+p) \leq 0.8$ (BeV/c)^2, the events consist almost entirely of $N^{*++}(1238)$. Figures 1(c) and 1(d) show the distributions in $M(\pi^+\pi^-)$. In this case, a strong ρ^0 peak is observed only in those events not containing an $M(\pi^+p)$ in the N^{*++} interval. Consequently, all events with $M^2(\pi^+p)$ in the interval 1.30 to 1.79 (BeV)^2 have been suppressed so that background in the $\rho^0\pi^-p$ final state is greatly reduced for the subsequent analysis. The shaded part of Fig. 1(d) indicates that most events with low momentum transfer to the proton, $\Delta^2(p) \leq 0.65$ (BeV/c)^2, contain at least one $M(\pi^+\pi^-)$ which may be ascribed to ρ^0 decay.

The $\pi^-\pi^+\pi^-$ effective-mass distribution is given in Fig. 2(b). Two clearly resolved peaks are observed above the 3π phase-space background: the first at 1090 MeV with full width $\Gamma \simeq 150$ MeV, the second at 1310 MeV with $\Gamma \simeq 80$ MeV. It is important to note that as long as the trend of the background is as indicated, the exact normalization does not affect the existence of the two peaks; however, the widths will be underestimated if the normalization is too large. To demonstarate that the peaks are associated primarily with $\rho^0\pi^-$, events with $\Delta^2(p) \leq 0.65$ (BeV/c)^2 are shown separately. Although the background has been markedly decreased by this selection, little reduction occurs in the peaks.

In order to search for $K\bar{K}$ decays that might be related to either 3π peak, all candidates for $K^-K_1^0p$ and $K_1^0K_1^0n$ final states were measured in 120 000 pictures at 3.2 BeV/c and 60 000 pictures at 4.2 BeV/c. The effective-mass distributions for the fitted events are shown in Fig. 2(a). The combined $K^-K_1^0$ and $K_1^0K_1^0$ distributions show an enhancement of approximately five standard deviations in the 1260- through 1380-MeV interval. This peak corresponds closely in position and width with the higher peak in the $\pi^-\pi^+\pi^-$ events, providing additional evidence for the presence of two distinct effects. Consequently, we conclude that a previously unresolved meson exists with $M = 1310$ MeV, $\Gamma \simeq 80$ MeV, and $I = 1$, which decays into $\pi\rho$ and $K\bar{K}$. Decay into $\pi\rho$ implies $G = -1$; for the observed $K\bar{K}$ decays, $G = (-1)^{L+I}$, so that $L = 0^+, 2^+, 4^+$, etc.[4] Consequent-

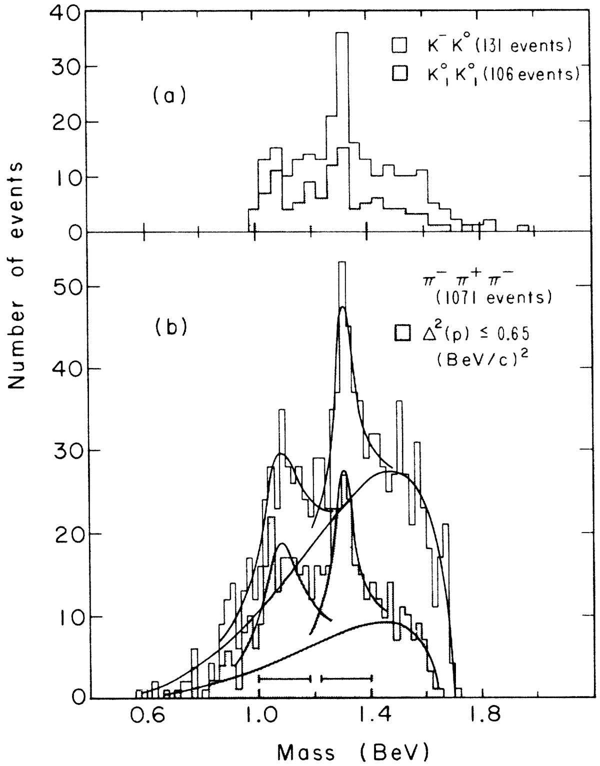

FIG. 2. Effective-mass distributions for (a) $K^-K_1^0$ and $K_1^0K_1^0$ pairs; (b) $\pi^-\pi^+\pi^-$ combinations for events with $M(\pi^+p)$ outside the N^{*++} interval. The smooth curves represent 3π phase space normalized to events outside the peaks. Bars indicate mass intervals used in the Dalitz plots.

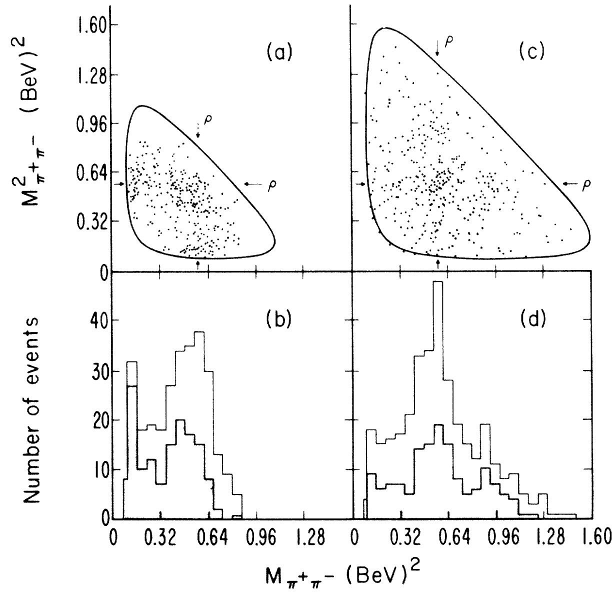

FIG. 3. (a, b) Dalitz plot for events with $M(\pi^-\pi^+\pi^-)$ between 1.00 and 1.18 BeV, and projection onto the $M^2(\pi_2^+\pi_3^-)$ axis; (c, d) Dalitz plot for events with $M(\pi^-\pi^+\pi^-)$ between 1.22 and 1.40 BeV, with projection onto $M^2(\pi_2^+\pi_3^-)$ axis. The shaded areas are projections for ρ^0 bands only, $M(\pi_1^-\pi_2^+)$ between 0.64 and 0.86 BeV. Events with $\Delta^2(p) > 0.65$ (BeV/c)^2 and $M(\pi^+p)$ in the N^{*++} interval are not shown. The solid curves represent the phase-space limits for 1.18 BeV in (a) and 1.40 BeV in (c).

ly, the lowest possible spin assignment is $J^{PG} = 2^{+-}$, since 3π decay of a $J^{PG} = 0^{+-}$ state is forbidden. No significant $K\bar{K}$ enhancement is apparent in the region of the 1090-MeV $\pi^-\pi^+\pi^-$ peak.

Although decay of the 1310-MeV peak into $K^- + K_1^0$ is clear, further discussion of the $K_1^0K_1^0$ enhancement is necessary. It has been noted that both $\pi^-\pi^+\pi^-$ peaks persist at low $\Delta^2(p)$, so production probably results from peripheral collisions involving ρ exchange. In this case we may expect $\pi^0{}^,{}^-\rho^-{}^,{}^0p:\pi^\pm\rho^\mp n \simeq 1:2$ and correspondingly $K^-K_1^0 \simeq K_1^0K_1^0$, in good agreement with the observed relative enhancements after correction for K_1^0 detection efficiency. However, $K_1^0K_1^0$ events may also result from decay of the $I=0, J^{PG} = 2^{++}$, f^0 meson with $M = 1250$ MeV and $\Gamma \simeq 140$ MeV.[5] A fit of the observed $K_1^0K_1^0$ distribution to a phase-space background plus a Breit-Wigner resonance centered at 1250 MeV yields a confidence level less than 5%. Consequently, it is likely that the observed $K_1^0K_1^0$ enhancement between 1260 and 1340 MeV represents the decay of the neutral component of the 1310-MeV state.

With the assignment $J^{PG} = 2^{+-}$ for the 1310-MeV state, the dominant features of the Dalitz plot are determined. To minimize background, we show only events with $\Delta^2(p) \leq 0.65$ (BeV/c)^2 in Fig. 3(c); for convenience in comparison with theory, each event is plotted twice. The general properties of 3π decays of unstable particles have been discussed by Zemach for arbitrary spin-parity assignments.[6] He shows that the matrix element for decay of an $I = 1$ or 2 state through an intermediate $\pi\rho$ may be written

$$M(\pi_1^-\pi_2^+\pi_3^-) = M_{1,23} - M_{3,12}, \qquad (1)$$

where $M_{k,lm}$ is an antisymmetric function in lm. If momenta in the 3π center of mass are $\vec{p}_1$, $\vec{p}_2$, and $\vec{p}_3$, and for $\vec{q} = \vec{p}_1 \times \vec{p}_3$, the simplest matrix elements for the $J^P = 1^-$ and 2^+ states may be calculated by using

$$\text{for } 1^-,\ M_{k,lm} = \alpha_k \vec{q}, \qquad (2a)$$

$$\text{for } 2^+,\ M_{k,lm} = \alpha_k(\vec{p}_k\vec{q} + \vec{q}\,\vec{p}_k), \qquad (2b)$$

where

$$\alpha_k \simeq (\Gamma_\rho/2\pi)^{1/2}[M_{lm}{}^2 - M_\rho{}^2 + iM_\rho\Gamma_\rho + (\Gamma_\rho/2)^2]^{-1}.$$

The presence of the axial vector $\vec{q}$ requires that the density vanish at the edge of the plot in either case. However, for 1^-, the density must also vanish along the entire line $M^2(\pi_1{}^-\pi_2{}^+) = M^2(\pi_2{}^+\pi_3{}^-)$.[7] Explicit calculation indicates that the width of the destructive interference in the overlapping ρ bands is $\simeq \Gamma_\rho$. In contrast, for 2^+, the highest density occurs in the overlapping ρ bands. The substantial background in Fig. 3(*c*) tends to mask the vanishing of the ρ bands towards the edge of the plot; however, within statistics, the highest density occurs where expected for the 2^{+-} assignment.

The Dalitz plot for the 1090-MeV peak is given in Fig. 3(a). In the projected distribution, Fig. 3(b), a marked enhancement is apparent at low $M^2(\pi^+\pi^-)$. Since this peak is concentrated in the ρ^0 bands, it is probably not associated with the small background of non-ρ^0 events. Consequently, neither the 1^- nor 2^+ assignment fits the present data. With no observed decay into $K\bar{K}$, other possible assignments are $J^P = 0^-, 1^+, 2^-$ etc. The pertinent matrix elements are obtained by using

$$\text{for } 0^-,\ M_{k,lm} = \alpha_k \vec{p}_k\cdot(\vec{p}_l - \vec{p}_m), \tag{3a}$$

$$\text{for } 1^+,\ M_{k,lm} = \alpha_k(\vec{p}_l - \vec{p}_m), \tag{3b}$$

$$\text{for } 2^-,\ M_{k,lm} = \alpha_k[\vec{p}_k(\vec{p}_l - \vec{p}_m) + (\vec{p}_l - \vec{p}_m)\vec{p}_k - (\tfrac{2}{3})I\,\vec{p}_k\cdot(\vec{p}_l - \vec{p}_m)], \tag{3c}$$

where I is a unit dyadic. The expected densities in the ρ bands are readily estimated. In the absence of Bose statistics (approximately valid outside the overlapping ρ bands) the decay angular correlations are as follows: for 0^-, $\cos^2\theta$; for 1^+, isotropic; for 2^-, $1 + (\frac{1}{3})\cos^2\theta$; where $\cos\theta = \vec{p}_k\cdot(\vec{p}_l - \vec{p}_m)/|\vec{p}_k||\vec{p}_l - \vec{p}_m|$ as measured in the $\pi_l\pi_m$ rest frame. Since the Dalitz plot is linear in $\cos\theta$ for a given $\pi_1{}^-\pi_2{}^+\pi_3{}^-$ energy and fixed p_1, the density distributions for low $M^2(\pi_2{}^-\pi_2{}^+)$ are apparent. The depopulation observed in the ρ bands at $M^2(\pi^+\pi^-) \sim 0.32\ (\text{BeV})^2$ is expected only for $J^{PG} = 0^{--}$. Both $J^{PG} = 1^{+-}$ and 2^{--} appear unlikely.[8]

The possibility for peaks in meson systems due to the Peierls mechanism has been discussed by Nauenberg and Pais[9] and Oakes.[10] They predict an enhancement in the $\pi\rho$ system in the region 1090 through 1125 MeV. However, the peak will not represent a state of pure J^P or I. The present data are not sufficient to determine whether the lower $\pi\rho$ enhancement arises from this mechanism. For convenience, we shall retain the term A meson used by Goldhaber et al. for this peak.[3] If the peak represents a pure state with $M_A = 1090$ MeV and $\Gamma_A \simeq 150$ MeV, the assignment $J^{PG} = 0^{--}$ is preferred.

Since the Peierls mechanism cannot generate two peaks, it is likely that the enhancement at 1310 MeV with $\Gamma \simeq 80$ MeV represents a pure state, with the data indicating the assignment $I = 1$, and $J^{PG} = 2^{+-}$. It has recently been pointed out by Pignotti that if bootstrap dynamics can account for an octet of 1^- mesons, the existence of a 2^+ octet is implied.[11] Consequently, we shall use the name R meson for the 1310-MeV state, as suggested by Pignotti for the $S = 0, I = 1$ member of the octet.

It is a pleasure to thank Professor Charles Zemach for helpful discussion on his paper, and Professor Arthur Rosenfeld for calling our attention to the full implications of the observed $K\bar{K}$ decays. We are grateful to Professor Luis Alvarez for his continued interest and encouragement. We are indebted to Mr. Werner Koellner and Mrs. Cathy Bowers and the scanning and measuring staffs for their untiring efforts in processing of the data. Of equal importance was the patient cooperation of the bubble-chamber crews under the direction of Mr. Robert Watt and the Bevatron crews directed by Dr. Edward Lofgren.

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

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[5]These are values for $f^0 \to \pi^+ + \pi^-$ reported by Y. Y. Lee, B. P. Roe, D. Sinclair, and J. C. Vander Velde, Phys. Rev. Letters 12, 342 (1964). N. Gelfand, G. Lütjens, M. Nussbaum, J. Steinberger, H. O. Cohn, W. M. Bugg, and B. T. Condo, Phys. Rev. Letters 12, 567 (1964), obtain $M(f^0) = 1225$ MeV and $\Gamma(f^0) = 150$ MeV. Although the width for the decay $f^0 \to K + \bar{K}$ will not be significantly affected, phase space plus the centrifugal barrier will tend to displace the mean mass to a higher value. We have not tried to take this effect into account, but merely use the higher mass value of Lee et al.

[6]Charles Zemach, Phys. Rev. 133, B1201 (1964).

[7]The importance of Bose-statistics effects in analysis of the $\pi\rho$ enhancement was exploited first by R. L. Lander, M. Abolins, D. D. Carmony, T. Hendricks, N. Xuong, and P. Yager (to be published). Since they assumed that the 1.0- to 1.4-BeV $\pi\rho$ enhancement is a single peak, their conclusions are markedly different from those presented here.

[8]It must be emphasized that these statements are valid only (a) for pure states, and (b) if the crucial regions of the Dalitz plot are not preferentially populated with background from $\rho^0 N^{*0}$ for nonresonant $\pi^-\rho^0 p$ events. Additional information is available from correlations in production and decay. However, more extensive data are required before these correlations can be studied in adequate detail.

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Λ-p ELASTIC SCATTERING*

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(Received 27 April 1964)

This Letter is a report of the Λ-p elastic cross section in the laboratory momentum range of 150 to 400 MeV/c. At present four measurements of the Λ-p elastic cross section have been reported in the literature.[1-4] Wide momentum ranges and low statistics have made it difficult to discriminate between several theoretical potentials. The data presented in this paper enable us to draw some conclusions regarding these potentials.

The experiment was carried out in the Berkeley-Powell 30-in. heavy liquid bubble chamber filled with a mixture of 76% CF_3Br and 24% C_3H_8 by weight. The Λ's were produced in the interaction K^- + nucleus → Λ + fragments. A total of 45 000 frames was double scanned to give 15 000 Λ's with an average path length of 1.66 cm. A random sample of 250 nonscattered Λ's was measured to provide the momentum distribution, plotted in Fig. 1, and the scanner efficiency. The sample events were then analyzed using the FOG-CLOUDY-FAIR data reduction programs developed by White and his group at Lawrence Radiation Laboratory.

The scanning criteria required that the proton and pion from the decay of the Λ remain in the chamber. From range-momentum curves the scanners could construct a vector diagram to determine the direction of the Λ. They could then decide if any possible recoil protons lay along the flight path of the Λ. The total number of events found by the scanners was reduced by 30%, since this percentage of the measured sample did not meet the required chi-squared criteria.

It was necessary to investigate what biases

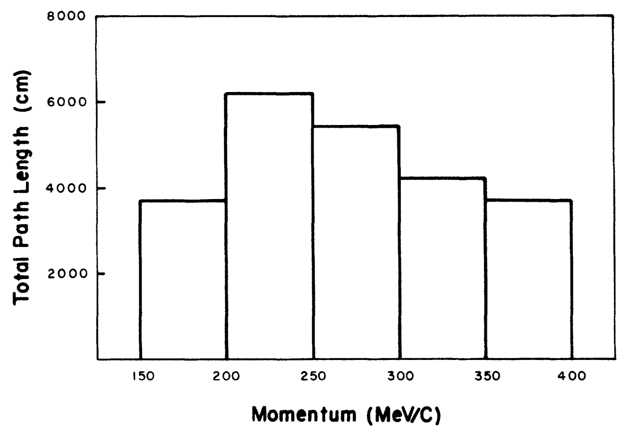

FIG. 1. Momentum plotted vs total path length. This distribution was obtained from the sample events and normalized to the total number of events.

would be induced from the requirement that both the proton and pion from the decay of the Λ stop in the chamber. This correction was accomplished by the use of a Monte-Carlo program which generated events corresponding to the two configurations observed, i.e., one where the Λ scatters and one where it does not. The program generated Λ's which obeyed distributions obtained from the sample events. These distributions were the coordinates of the K interaction, the azimuthal and dip angles of the Λ, the lifetime of the Λ, and its momemtum. A sample of 1000 events for each configuration (scattered and unscattered) was generated by the program. The end points of the proton and pion were calculated and then checked to determine if they remained in the chamber. The ratio of observed nonscatters to observed scat-

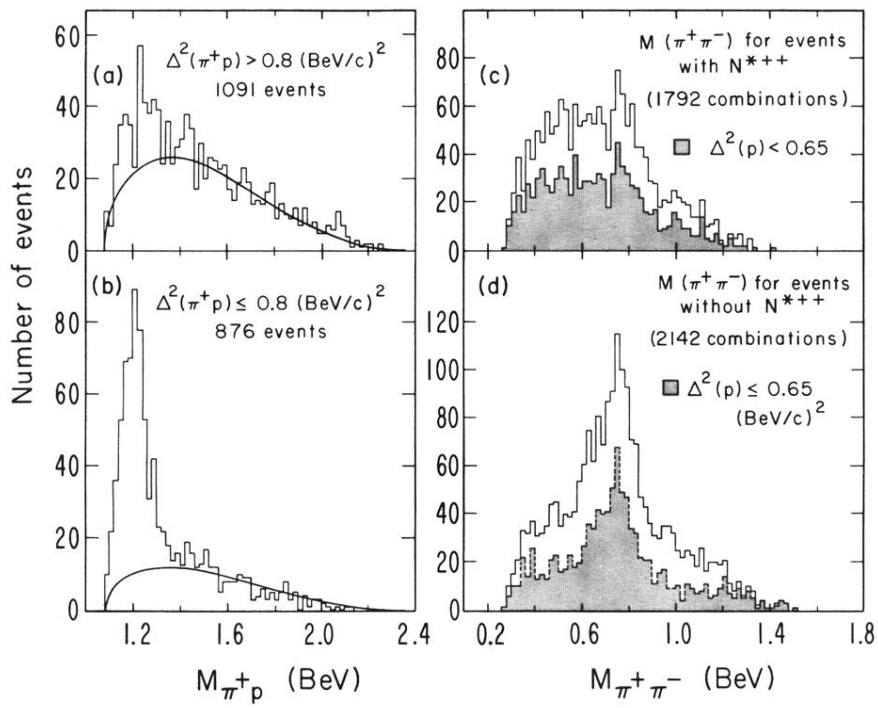

FIG. 1. Effective-mass distributions for (a, b) π^+p combinations at high and low momentum transfer; (c, d) $\pi^+\pi^-$ combinations with and without N^{*++}.

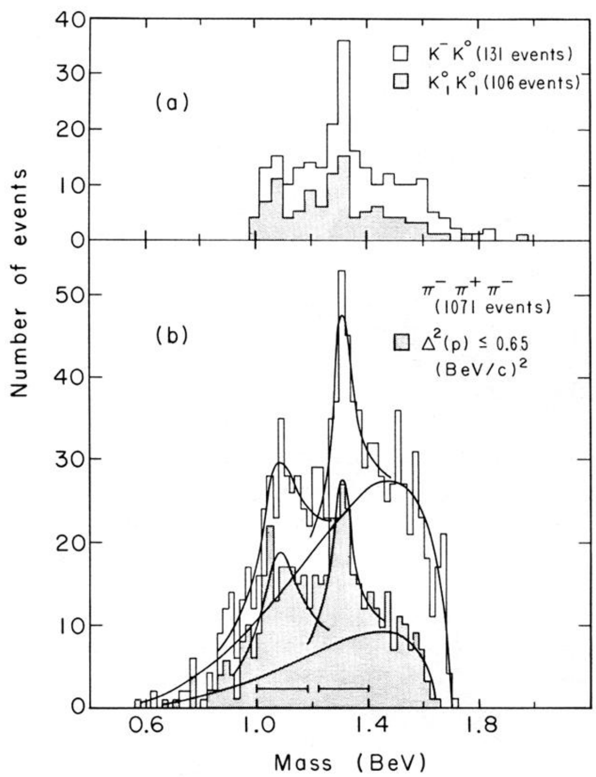

FIG. 2. Effective-mass distributions for (a) $K^-K_1^0$ and $K_1^0K_1^0$ pairs; (b) $\pi^-\pi^+\pi^-$ combinations for events with $M(\pi^+p)$ outside the N^{*++} interval. The smooth curves represent 3π phase space normalized to events outside the peaks. Bars indicate mass intervals used in the Dalitz plots.

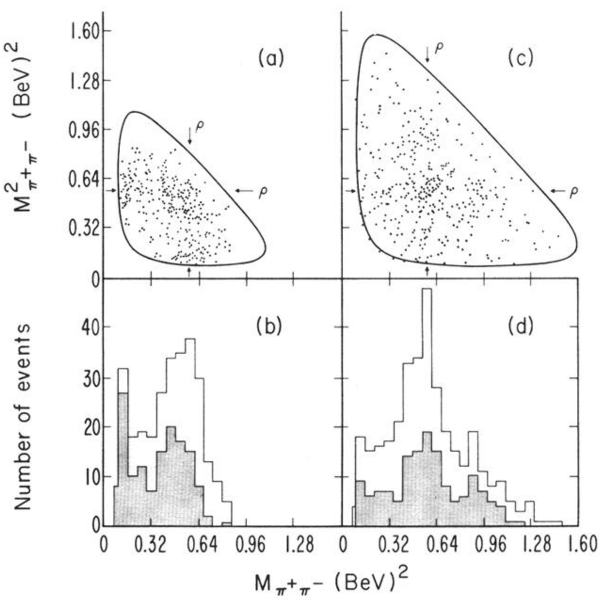

FIG. 3. (a, b) Dalitz plot for events with $M(\pi^-\pi^+\pi^-)$ between 1.00 and 1.18 BeV, and projection onto the $M^2(\pi_2{}^+\pi_3{}^-)$ axis; (c, d) Dalitz plot for events with $M(\pi^-\pi^+\pi^-)$ between 1.22 and 1.40 BeV, with projection onto $M^2(\pi_2{}^+\pi_3{}^-)$ axis. The shaded areas are projections for ρ^0 bands only, $M(\pi_1{}^-\pi_2{}^+)$ between 0.64 and 0.86 BeV. Events with $\Delta^2(p) > 0.65$ (BeV/c)^2 and $M(\pi^+p)$ in the N^{*++} interval are not shown. The solid curves represent the phase-space limits for 1.18 BeV in (a) and 1.40 BeV in (c).