Phys. Rev. Letters 3, 433 (1959).
[7]F. W. K. Firk and K. H. Lokan, Phys. Rev. Letters 8, 321 (1962).
[8]C. Milone and A. Rubbino, Nuovo cimento 13, 1035 (1959).
[9]S. A. E. Johansson and B. Forkman, Arkiv Fysik 12, 359 (1957).
[10]P. Brix and E. K. Maschke, Z. Physik 155, 109 (1959).
[11]D. L. Livesey, Can. J. Phys. 34, 1022 (1956).
[12]W. R. Dodge and W. C. Barber, Phys. Rev. 127, 1746 (1962).
[13]J. Miller, G. Schuhl, G. Tamas, and C. Tzara, Phys. Letters 2, 76 (1962).
[14]B. M. Spicer, Australian J. Phys. 10, 326 (1957).
[15]K. N. Geller, Phys. Rev. 120, 2147 (1960).
[16]V. Gillet and N. Vinh Mau, Phys. Letters 1, 25 (1962).
[17]G. E. Brown, L. Castillejo, and J. A. Evans, Nuclear Phys. 22, 1 (1961).
[18]M. Bauer, Ph.D. thesis, University of Maryland, 1962 (unpublished).
[19]F. Ferrero, R. Malvano, S. Menardi, and O. Terracini, Nuclear Phys. 9, 32 (1958).
[20]J. E. E. Baglin, N. M. Thompson, and B. M. Spicer, Nuclear Phys. 22, 207 (1961).
[21]J. Dular, G. Kernel, M. Kregar, M. V. Mihailovic, G. Pregl, M. Rosina, and C. Zupancic, Nuclear Phys. 14, 131 (1959).
[22]B. Ziegler, Nuclear Phys. 17, 239 (1960).

FINAL-STATE INTERACTIONS IN THE $\pi^- + p \to K + \bar{K} + N$ REACTION*

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In this Letter we report results of a study of the reaction $\pi^- + p \to K + \bar{K} + N$ at incident momenta less than 2.3 BeV/c. We find that the distribution in momentum transfer to the recoil nucleon is consistent with the assumption that most $K\bar{K}$ pairs are produced in peripheral $\pi^- + p$ collisions, as suggested by the data of Erwin et al.[1] However, the effective-mass distributions for the $\bar{K}N$ system indicate that an additional contribution to the $K\bar{K}N$ final state arises from production of the isotopic spin $I=0$ resonant state Y_0^*(1520 MeV),[2] with the subsequent decay $Y_0^* \to \bar{K} + N$. We have also examined the $K\bar{K}$ effective-mass distributions for possible effects due to final-state interactions. Although the K^0K^- effective-mass distribution is consistent with the phase-space estimate, an enhancement is observed for the neutral $K\bar{K}$ system (K_1K_1n final states) in the region $M^2(K_1K_1) \simeq (1.02\ \text{BeV})^2$. A satisfactory fit to the data is obtained if the enhancement is attributed to strong scattering in the $I=0$, S-wave $K\bar{K}$ state. In a study of the reaction $K^- + p \to \Lambda + K + \bar{K}$ at 2.24 and 2.5 BeV/c, Bertanza et al. have observed a similar enhancement at approximately the same mass; however, only final states of the type ΛK_1K_2 were found.[3] The relation of the two results is discussed.

The data were obtained during an extensive exposure of the Lawrence Radiation Laboratory's 72-in. hydrogen bubble chamber to a secondary π^- beam at six momentum settings ranging from 1.51 to 2.25 BeV/c. A total of 225 000 pictures with 10 to 20 π^- mesons each were taken and scanned for visible production of strange particles. Of the 12 000 events measured, 158 were unambiguously identified via the kinematical constraint program PACKAGE as belonging to one of the following hypotheses:

(a) $\pi^- + p \to K^0 + K^- + p$, with $K^0 \to \pi^+ + \pi^-$;

(b) $\pi^- + p \to K^0 + \bar{K}^0 + n$,
with $K^0 \to \pi^+ + \pi^-$,
and $\bar{K}^0 \to \pi^+ + \pi^-$.

The number of observed events together with the approximate path length examined is summarized in Table I.

The Dalitz plot for the reaction $\pi^- + p \to K^0 + K^- + p$, together with its projections on the $M^2(K^0K^-)$ and $M^2(K^-p)$ axes, is shown in Fig. 1. Since the effects of two-body interactions may be obscured in events occurring too close to the kinematic threshold, all events for which the laboratory momentum of the incident pion p_π is less than 1.95 BeV/c have been plotted separately and are not used in the analysis of effective-mass distributions. The phase-space curves represent weighted averages for the data appearing in the plots. A strong enhancement appears in the $M^2(K^-p)$ distribution at $M^2 \simeq (1520\ \text{MeV})^2$, with estimated full width $\Gamma \simeq 25$ MeV. Since the resonant state, Y_0^*(152 MeV, is readily produced in the π^- momentum

Table I. The number of observed events at each beam-momentum setting together with the path length examined.

Beam momentum (BeV/c)	Number of observed events K^0K^-p	$K^0\bar{K}^0n$	Path length (10^5 meters)
1.51	0	0	5.1
1.69	2	7	6.4
1.89	16	10	10.1
2.05	13	8	3.4
2.17	24	18	12.2
2.25	37	23	15.2
Total	92	66	

interval studied here,[4] we attribute the peak to the reaction $\pi^- + p \to Y_0^* + K^0$ followed by $Y_0^* \to K^- + p$. No significant deviation from the phase-space curve is observed for either the $M^2(K^0K^-)$ or the $M^2(K^0p)$ distribution.

The Dalitz plot for the reaction $\pi^- + p \to K^0 + \bar{K}^0 + n$ is shown in Fig. 2. In the present experiment we can fit only those events for which both the K^0 and $\bar{K}^0$ decay via the $K_1 \to \pi^+ + \pi^-$ mode; interactions leading to the K_1K_2n final states are kinematically underdetermined, since neither the neutron nor the K_2 is observed.[5] In addition, the K^0

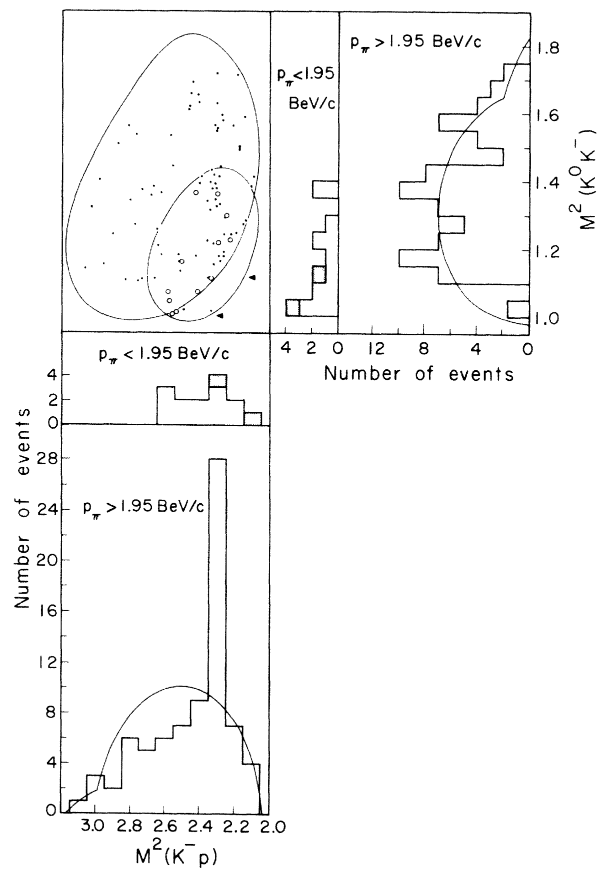

FIG. 1. Dalitz plot for $\pi^- + p \to K^0 + K^- + p$. Phase-space curves are normalized to the total number of events. Events for incident pion momenta, p_π, less than 1.95 BeV/c are projected separately. The shaded areas correspond to $p_\pi < 1.78$ BeV/c. See text for details.

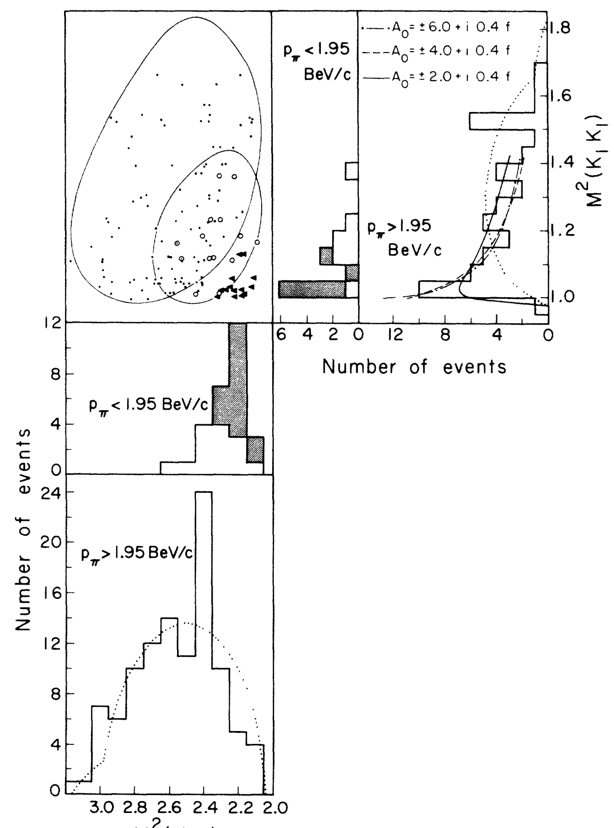

FIG. 2. Dalitz plot for $\pi^- + p \to K_1 + K_1 + n$. Each event yields two points on the plot. Phase-space curves (dotted) are normalized to the total number of events with $p_\pi > 1.95$ BeV/c. The effect of strong $I = 0$, S-wave $K\bar{K}$ scattering is indicated for several values of the complex scattering length $A_0 = a_0 + ib_0$. See text for details.

cannot be distinguished from the $\bar{K}^0$, so that each event must be represented by two points on the Dalitz plot. The distribution for $M^2(K^0\bar{K}^0)$ is still unique and may be compared directly with the $M^2(K^0K^-)$ distribution; in the other projection we are constrained to study the sum of the distributions for $M^2(K^0n)$ and $M^2(\bar{K}^0n)$. It must be noted that if the product CP is conserved in production and decay, the observed K_1K_1 events result only from those states in which the relative angular momentum, L, of the neutral $K\bar{K}$ system is even. Consequently, the K_1K_1n events serve as a detector for only a restricted portion of the $K^0\bar{K}^0n$ final state.

A comparison of the $M^2(K_1K_1)$ distribution with the phase-space curve indicates a systematic tendency for the K_1K_1 system to be produced with low effective mass, a peak occurring in the region $M^2(K_1K_1) \simeq (1.02\ \text{BeV})^2$. Since no corresponding deviation is observed in the K^0K^-p events, we ascribe the effect to a strong interaction in the $I=0$ $K\bar{K}$ system.[6] Possible assignments for the enhanced state are 0^{++}, 2^{++}, etc. (spatial parity is designated by the first superscript and G-parity by the second). This result may be compared to the similar enhancement reported by Bertanza et al., in which no K_1K_1 final states were observed. With CP conservation, the difference in decay states is sufficient to conclude that the observed enhancements must arise from strong interactions occurring in two states of the neutral $K\bar{K}$ system with opposite parity.

The combined $M^2(K^0n)$ and $M^2(\bar{K}^0n)$ distributions have been examined for evidence of the decay $Y_0^* \to \bar{K}^0+n$. Taking into account $\Gamma(Y_0^* \to K^-+p)/\Gamma(Y_0^* \to \bar{K}^0+n)=1$, and the relative detection efficiencies, 3:1, for K^0K^-p and $K^0\bar{K}^0n$ final states due to K^0 decay, the ~$20\,Y_0^*$(1520 MeV) decays observed in the K^0K^-p channel lead to the expectation that ~7 ± 1.5 $K^0\bar{K}^0n$ events will be associated with Y_0^* decay. Although we observe no enhancement in the M^2 interval centered about 1520 MeV, a peak of about 12 counts is present in the next higher interval. Although this M^2 distribution may arise from a series of statistical fluctuations, the shift in the position of the Y_0^*(1520 MeV) resonance may be due to interference with the strong $K^0\bar{K}^0$ interaction.

The distributions for the cosine of the nucleon recoil angle in the π^-+p c.m. system, and the invariant momentum transfer to the nucleon, Δ^2, are given in Fig. 3. Chew and Low have shown that if one-pion exchange (OPE) contributes to Reactions (a) and (b), the double-differential cross

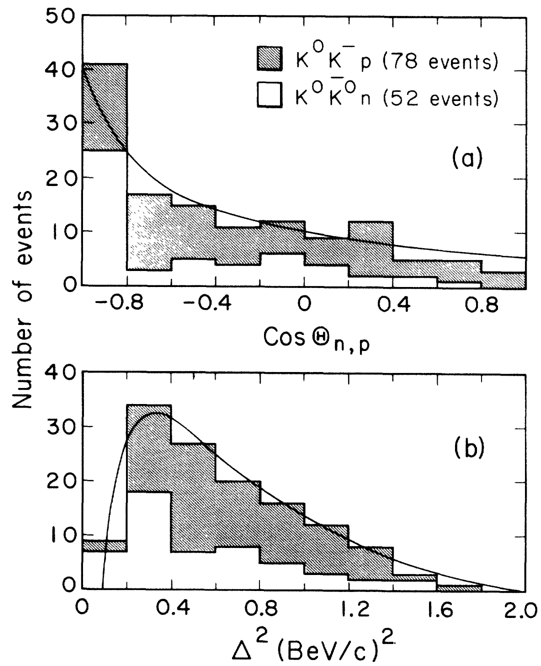

FIG. 3. Production c.m. angular distribution and invariant momentum transfer, Δ^2, for the recoil nucleon. The solid curves were calculated assuming that $K\bar{K}$-pair production occurs in peripheral collisions. Data are for $p_\pi > 1.95$ BeV/c. Elimination of events possibly associated with Y_0^* decay results in no significant change in the distributions.

section is dominated in the limit $\Delta^2 \to -m_\pi^2$ by the term[7]

$$\frac{d^2\sigma}{d\Delta^2 dM^2} = \frac{f^2}{2\pi}\frac{Mk_\pi}{M_\pi^{\ 2}p_\pi}\frac{\Delta^2}{(\Delta^2+M_\pi^{\ 2})^2}\sigma(\pi\pi\to K\bar{K}), \qquad (1)$$

where M is the effective mass of the $K\bar{K}$ system, f is the π-N coupling constant ($\times 2^{1/2}$ for π^+ exchange), k_π(or k_K) is the momentum of either pion (or either K meson) in the $\pi\pi$ c.m. system, and $\sigma(\pi\pi\to K\bar{K})$ is the $K\bar{K}$ production cross section at energy M for the appropriate initial and final charge states. The solid curves in Figs. 3(a) and 3(b) were obtained by suitable integrations over $M^2(K\bar{K})$, where we have taken $\sigma(\pi\pi\to K\bar{K}) \propto k_K/k_\pi$ and Eq. (1) to be valid for physical values of Δ^2. Agreement with the data is satisfactory. In addition, Treiman and Yang have pointed out[8] that for reactions occurring peripherally, there can be no correlation between directions defined in the rest frame of the incident pion by $\vec{p}_0\times\vec{p}_f$ (initial and final nucleon momentum) and $\vec{p}_K\times\vec{p}_{\bar{K}}$. After subtraction of events associated with Y_0^*(1520 MeV) decay, the distribution in the angle $\psi = \cos^{-1}(\vec{p}_0 \times \vec{p}_f \cdot \vec{p}_K \times \vec{p}_{\bar{K}})$ for all remaining events is uniform within statistics.

If the adequacy of the OPE mechanism is accepted for $K\bar{K}$ productions not associated with Y_0^* decay, Eq. (1) may be used to estimate the cross sections for $\pi + \pi \to K + \bar{K}$.[9] In particular, we shall consider the strongly interacting $I=0$ state. Since the enhancement in $M^2(K_1K_1)$ occurs close to the $K^0\bar{K}^0$ threshold,[10] it is possible that it may arise from strong S-wave scattering in the $K\bar{K}$ system.[11] For simplicity we take into account only the two channels $K\bar{K} \leftrightarrow K\bar{K}$, and $K\bar{K} \leftrightarrow \pi\pi$. Using the zero-effective-range approximation[12] and detailed balancing, we can write the S-wave $K\bar{K}$ production cross section for pure $I=0$ initial and final states:

$$\sigma_0(\pi\pi \to K\bar{K}) = (4\pi k_K/k_\pi^2)2b_0/[(1+b_0k_K)^2 + (a_0k_K)^2], \quad (2)$$

where $A_0 = a_0 + ib_0$ is the $I=0$, S-wave, $K\bar{K}$ scattering length. The additional factor of two arises from symmetrization of the initial and final states. Since we assume that the $K\bar{K}$ system is produced in the S wave, one fourth of the events will lead to the K_1K_1 final state.[13] Taking into account the isotopic composition of the initial $\pi^-\pi^+$ state, we obtain

$$\sigma(\pi^-\pi^+ \to K_1K_1) = (\tfrac{1}{3})(\tfrac{1}{4})\sigma_0(\pi\pi \to K\bar{K}). \quad (3)$$

Using Eqs. (1), (2), and (3), we have evaluated $d\sigma/dM^2$ for several combinations of a_0 and b_0. For normalization, it was assumed that all events with $M^2(K_1K_1)$ less than 1.3 BeV^2 were associated with the enhanced 0^{++} state. We find that $A_0 \simeq \pm(4$ to $6) + i0$ fermis provides an adequate fit to both the observed cross section[14] (determined predominantly by b_0) and the shape of the $M^2(K_1K_1)$ distribution.

It is a pleasure to acknowledge the advice and encouragement of Professor Luis Alvarez throughout the course of this experiment. In addition, the authors are indebted to the operators of the 72-in. bubble chamber and the Bevatron for their skill and patience. Finally, no result would be forthcoming without the enormous effort of our scanning and measuring staffs.

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[1]A. R. Erwin, G. A. Hoyer, R. H. March, W. D. Walker, and T. P. Wangler, Phys. Rev. Letters 9, 34 (1962).

[2]M. Ferro-Luzzi, R. D. Tripp, and Mason B. Watson, Phys. Rev. Letters 8, 28 (1962).

[3]L. Bertanza, V. Brisson, P. L. Connolly, E. L. Hart, I. S. Mittra, G. C. Moneti, R. R. Rau, N. P. Samios, I. O. Skillicorn, S. S. Yamamoto, M. Goldberg, L. Gray, J. Leitner, S. Lichtman, and J. Westgard, Phys. Rev. Letters 9, 180 (1962); (private communication).

[4]G. Alexander, G. R. Kalbfleisch, D. H. Miller, and G. A. Smith, Phys. Rev. Letters 8, 447 (1962).

[5]Some fraction of the $K_2 \to \pi + \mu + \nu$ decays may fit as $K_1 \to \pi^+ + \pi^-$. As a check for any serious contamination due to K_2 decays, the lifetime has been calculated for events used in the present analysis. We find $\tau = (0.86 \pm 0.08) \times 10^{-10}$ sec, consistent with a pure sample of K_1 decays [see, for example, G. Alexander, S. P. Almeida, and F. S. Crawford, Phys. Rev. Letters 9, 69 (1962), reference 11].

[6]The $I=1$ $K\bar{K}$ system can be produced from either the $I=\frac{1}{2}$ or $I=\frac{3}{2}$ component of the initial $\pi^- + p$ state; consequently destructive interference is possible in the K^0K^- channel. Because the data were obtained over a range of incident momenta, we consider such a complete accidental cancellation unlikely.

[7]G. F. Chew and F. E. Low, Phys. Rev. 113, 1640 (1959).

[8]S. B. Treiman and C. N. Yang, Phys. Rev. Letters 8, 140 (1962).

[9]These cross sections were estimated in reference 1. It may be noted that the cross sections of Erwin et al. are overestimated because k_K rather than k_π is used in the numerator of Eq. (1).

[10]In the absence of a strong $K\bar{K}$ interaction, explicit evaluation of Eq. (1) yields results for the expected $M^2(K\bar{K})$ distribution quite similar to the phase-space estimate. Consequently, conclusions based upon a comparison with the phase-space curves remain unchanged.

[11]The possibility that the enhancement arises from the decay of a zero-strangeness, $J=2^{++}$, resonant state cannot be ruled out. However, such a state may be expected to decay much more rapidly into two or four pions. Since no well-established peak has been observed in the neutral $\pi\pi$ system in the corresponding mass region, the hypothesis is not required by existing experimental data. It may be noted that to the extent that $K\bar{K}$-pair production occurs peripherally, the lowest relative angular momentum allowed to the K^0K^- system is $L=1$. The centrifugal barrier in this state may contribute to the tendency for the Dalitz plot (Fig. 1) to be depopulated as $M^2(K^0K^-) \to (M_{K^0} + M_{K^-})^2$.

[12]See, for example, R. H. Dalitz, Enrico Fermi Institute for Nuclear Studies Report EFINS-61-69 (unpublished).

[13]In addition to having $I=0$, the initial S-wave $\pi\pi$ state is even under charge conjugation, C. Since I and C are conserved in the peripheral collision, the final charge

state must be $\frac{1}{2}(K^0\bar{K}^0 + \bar{K}^0K^0) - \frac{1}{2}(K^+K^- + K^-K^+) = \frac{1}{2}(K_1K_1 + K_2K_2) - \frac{1}{2}(K^+K^- + K^-K^+)$ [see, for example, M. Goldhaber, T. D. Lee, and C. N. Yang, Phys. Rev. 112, 1796 (1958)].

[14]Using the path length given in Table I for $p_\pi > 1.95$ BeV/c, and correcting for the 10% electron and muon beam contamination, we estimate the contribution to the cross section to be 0.1 μb per event.

BINDING ENERGY OF Λ^0 HYPERONS IN HEAVY HYPERNUCLEI ($60 < A < 100$)*

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It has been shown by Jones et al.[1] that the short-range (<5 μ) hyperfragments resulting from 800-MeV/c K^--meson interactions in emulsion are, in fact, the spallation products of silver and bromine nuclei and possess mass values in the range from $A = 60$ to $A = 100$. From a study of the total visible energy release in the nonmesonic decays of these hypernuclei, an upper limit of about 35 MeV has been placed on the value of their B_Λ. From the observation of five π-mesonic decays which are attributed to hyperfragments of the same order of mass, a more precise estimation of this upper limit has been made, namely, about 25 MeV.

Two Ilford K5 emulsion stacks were exposed to the 800-MeV/c K^--meson beam at the Berkeley Bevatron. They were area scanned for beam stars. In a total of 17 000 stars, ~900 hyperfragments were found. For this work, 470 nonmesonic disintegrations of "spallation hyperfragments" were measured, among those where all prongs from the decay star could be well distinguished from those originating from the production star. The visible energy release in a decay was computed as the sum of kinetic and binding (taken as 8 MeV per particle) energies of each of the charged emitted particles, assumed to be protons. The resulting total visible energy release histogram is given in Fig. 1(a), Fig. 1(b) showing an enlarged view of the upper part of the spectrum. The available energy in these decays is $M_\Lambda - M_N - B_\Lambda + B_N \cong (184 - B_\Lambda)$ MeV. Thus the observation of a cutoff for total energy releases close to 150 MeV allows us to put an upper limit of about 35 MeV on B_Λ for this class of hypernuclei.[2]

The details of five π-mesonic decays which are attributed to the same type of hypernuclei are set out in Table I. These have been collected from stacks exposed to stopping K^- and 800-MeV/c K^- beams at the Berkeley Bevatron and to the 1.5-BeV/c K^- beam at the CERN proton synchrotron. In each of these events the total visible energy release is much smaller than that usually associ-

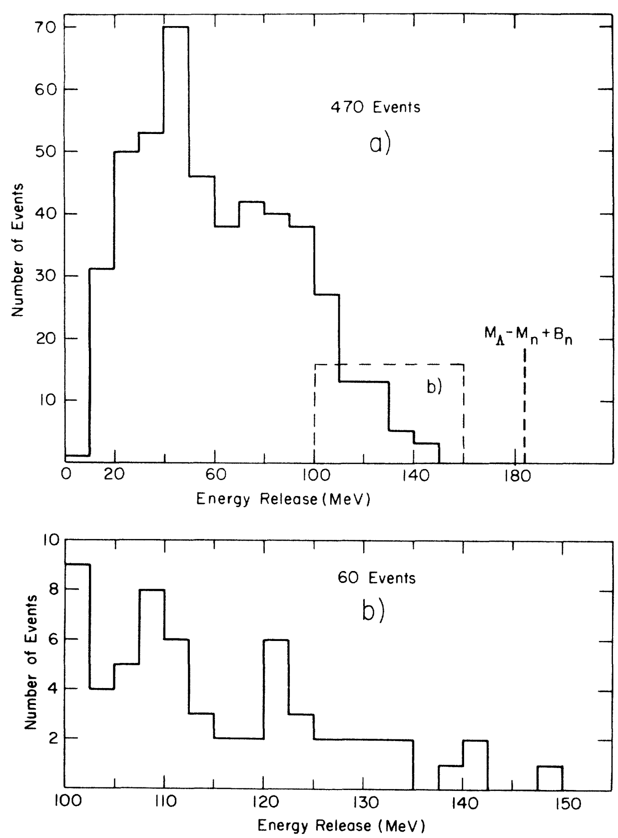

FIG. 1. Total visible energy release distribution for nonmesonic "spallation hyperfragment" disintegrations.

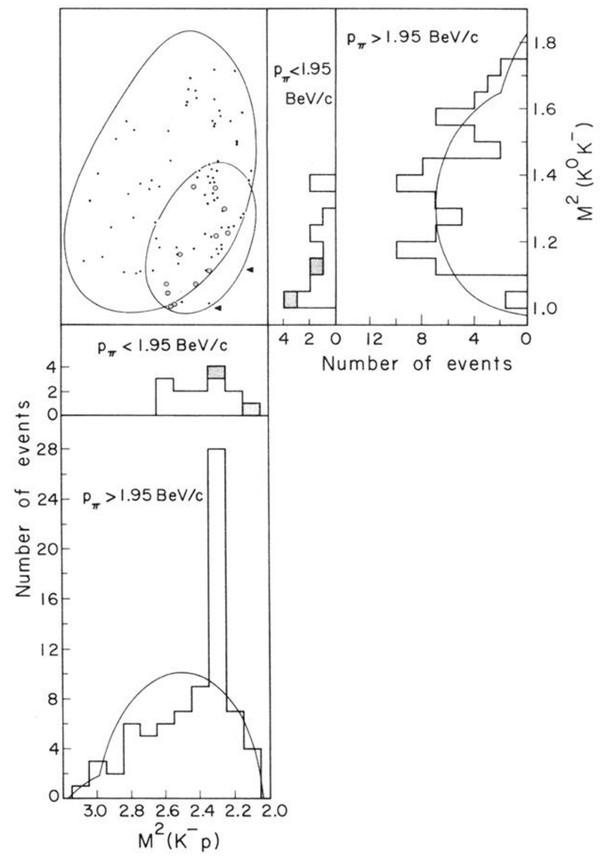

FIG. 1. Dalitz plot for $\pi^- + p \rightarrow K^0 + K^- + p$. Phase-space curves are normalized to the total number of events. Events for incident pion momenta, p_π, less than 1.95 BeV/c are projected separately. The shaded areas correspond to $p_\pi < 1.78$ BeV/c. See text for details.

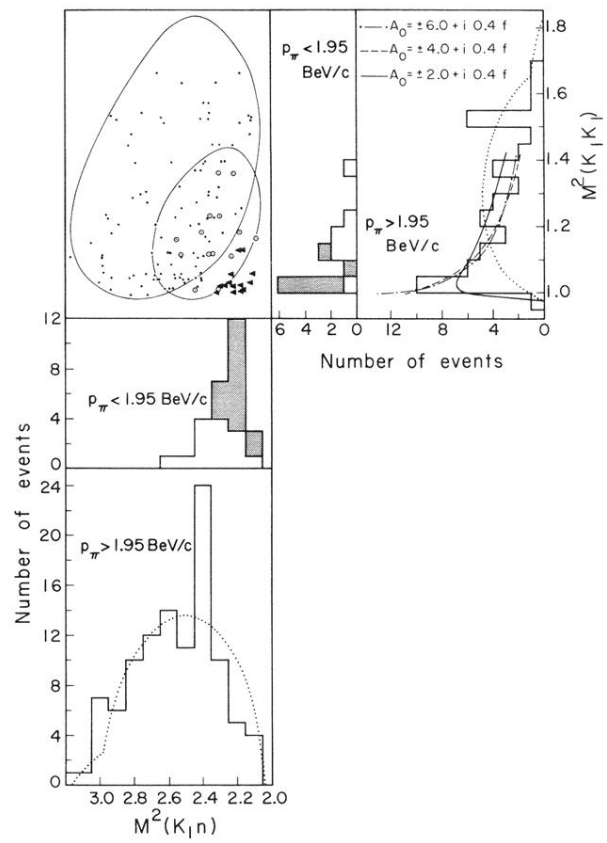

FIG. 2. Dalitz plot for $\pi^- + p \rightarrow K_1 + K_1 + n$. Each event yields two points on the plot. Phase-space curves (dotted) are normalized to the total number of events with $p_\pi > 1.95$ BeV/c. The effect of strong $I = 0$, S-wave $K\bar{K}$ scattering is indicated for several values of the complex scattering length $A_0 = a_0 + ib_0$. See text for details.

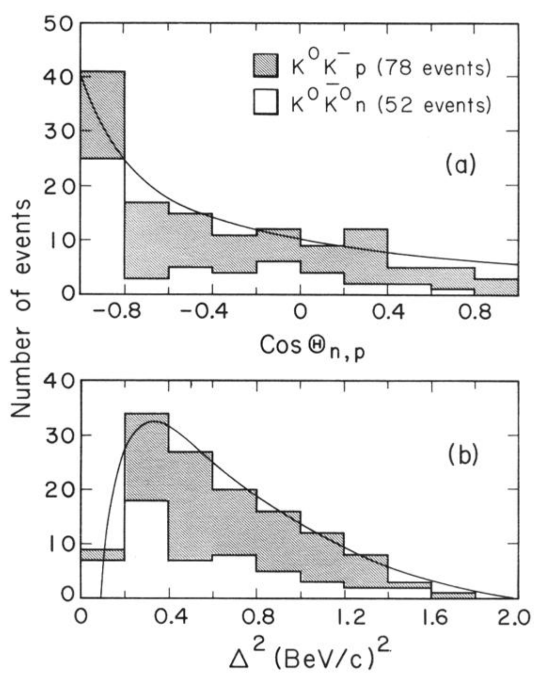

FIG. 3. Production c.m. angular distribution and invariant momentum transfer, Δ^2, for the recoil nucleon. The solid curves were calculated assuming that $K\bar{K}$-pair production occurs in peripheral collisions. Data are for $p_\pi > 1.95$ BeV/c. Elimination of events possibly associated with Y_0^* decay results in no significant change in the distributions.