EVIDENCE FOR A NON-STRANGE MESON OF MASS 1290 MEV

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In this letter we present evidence for the existence of a non-strange meson with a mass M = 1290 MeV and decaying into $K \bar{K} \pi$ final state and discuss possible quantum number assignments for this particle[1].

1) The results were obtained from an analysis of $\bar{p}p$ annihilations involving at least 1 visible K_1^o decay. The film under study was taken in the Saclay 81 cm HBC exposed to a beam of 1.2 GeV/c $\bar{p}$ from the CERN P.S.

The events presented represent the complete film sample. A detailed estimation of the path length is not yet available, but to roughly 20 % accuracy one event corresponds to a cross-section of 150 nanobarns.

In what follows, we limit our discussion to the following categories of events :

(1)	$\bar{p}p \to K_1^0 K^\pm \pi^\mp \pi^+ \pi^-$	323 ev.
(2)	$\bar{p}p \to K_1^0 K_1^0 \pi^+ \pi^- \pi^0$	326 ev.
(3)	$\bar{p}p \to K_1^0 K^\pm \pi^\mp M$	236 ev.
(4)	$\bar{p}p \to K_1^0 \pi^+ \pi^- M$	470 ev.
(5)	$\bar{p}p \to K_1^0 K^\pm \pi^\mp \pi^+ \pi^- \pi^0$	122 ev.
(6)	$\bar{p}p \to K_1^0 K^\pm \pi^\mp \pi^0$	1621 ev.

"M" in reactions (3) and (4) stands for the mass of 2 or more missing neutrals.

2) We discuss first reactions (1), (2), (3). Of the well established resonances only K^* and ω are produced copiously in these channels. Because of its narrow width we can subtract out easily the events showing ω production in reaction (2). In the subsequent discussion we limit ourselves only to the 182 examples of that reaction which remain after this subtraction.

The K^* (890) is produced especially strongly ($\sim$ 80 %) in reaction (1) ; its presence results in considerable deformation of the mass spectrum of the $(K\bar{K}\pi)$ system ; however, it does not affect sensitively the low mass region ($M < 1.350$ GeV).

Fig. 1 shows the combined effective mass squared distributions for all neutral, (fig. 1a) single (fig. 1b) and double (fig. 1c) charged $K\bar{K}\pi$ combinations available for reactions (1), (2) and (3). We have not included in fig. 1a the mass squared of the K^0M system from reaction (4) (fig. 1g) because of the impossibility of subtracting the ω events and the presence of the $K\bar{K}$ 4π events. Whereas the charged $K\bar{K}\pi$ combinations show no sharp deviations from smooth distributions, the spectrum of the neutral system shows a statistically significant, narrow peak, centered around $M^2 = 1.67$ GeV^2. Furthermore, within the statistics, the contribution to this peak comes from all of the first three reactions (fig. 1d, e, f). The same neutral spectrum (fig. 1a) shows a large enhancement in the region of the E-meson ($M^2 = 2.0$ GeV^2) observed in the $\bar{p}p$ annihilations at rest [2]. However, because of the difficulties associated with understanding the effect of the presence of K^*'s upon the $K\bar{K}\pi$ mass spectrum, we postpone the discussion of the possible production of the E-meson to a future publication.

3) We next turn to reaction $\bar{p}p \rightarrow K_1^o K^{\pm} \pi^{\mp}\pi^-\pi^o$. Examination of the neutral three-pion systems demonstrates that the ω-particle is strongly produced in this reaction. We observe again an enhancement in the neutral ($K\bar{K}\pi$) spectrum at $M^2 = 1.67$ GeV (fig. 2a). Furthermore, this effect is absent in the singly and doubly charged $K\bar{K}\pi$ combinations. We have investigated to what extent the $K\bar{K}\pi$ enhancement could be just a kinematical effect due to the production of the ω meson.

More specifically, we pose three questions :

α) Is the $K\bar{K}\pi$ enhancement seen only in those events which also contain an ω ?

β) If so is the $K\bar{K}$ enhancement merely a kinematical reflection of the fact that the pion in that system really forms an ω ?

γ) If objection β can be disposed of, can the $K\bar{K}\pi$ enhancement be interpreted merely as phase space peaking for the $K\bar{K}\pi\omega$ final state ?

Fig. 2b shows the mass squared spectrum of the neutral $K\bar{K}\pi$ systems for those events which do not contain ω. The absence of the peak at 1.67 GeV^2 demonstrates that the $K\bar{K}\pi$ effect is associated with ω events.

Fig. 2c and d show the mass squared spectrum of the neutral $K\bar{K}\pi$ systems for the events containing the ω. In fig. 2c that $K\bar{K}\pi$ combination was chosen whose pion does not form part of the ω ; the mass of the other $K\bar{K}\pi$ system was plotted in fig. 2d. The comparison of fig. 2c and d disposes of objection β. Furthermore, for the $K\bar{K}\pi\omega$ final state (fig. 2c), the experimental spectrum deviates from phase space in the region of 1.67 GeV by 2.3 standard deviations.

4) To summarize, we have observed in different annihilation channels a neutral $K\bar{K}\pi$ enhancement with no charged counterpart. The best estimate for the central value is 1290 $\pm$ 3 MeV, where the error quoted is merely statistical. An additional shift of up to 5 MeV due to systematic effects cannot be excluded. Our best estimate for the full width Γ is 25 MeV with an upper limit of 40 MeV. Furthermore, a study of the errors on the mass of the $\pi\pi\pi$ system and of the experimental width of the ω peak leads us to believe that the errors calculated in our analysis programs are not underestimated. If this is also true for the $K\bar{K}\pi$ system, then the natural width of the $K\bar{K}\pi$ peak is incompatible with zero. In view of these characteristics, in particular the narrowness of the width, we have ruled out the identification of this enhancement with the A_2-meson, although the range of mass presently assigned to the A_2-meson would allow, by itself, such an identification. Of course, this is a fortiori true for the f^o and B-mesons. Furthermore, agreement of the mass and width values of the $K\bar{K}\pi$ peak with those quoted by Miller et al.[1] leads us to conclude that we are observing the some phenomenon as the Berkeley group. Accordingly we shall henceforth refer to this effect as the D meson.

5) We discuss next the production mechanism of the D-meson. As remarked above, the dominant channel contributing to reaction (5) is the process :

$$\bar{p}p \rightarrow D^o\omega^o \qquad \text{18 events.}$$

For reactions (1) and (2), examination of the mass-spectrum of the recoiling $\pi^+\pi^-$ system for the events involving the D $\left(1.64 < M^2\ (K\bar{K}\pi) < 1.72\ \mathrm{GeV}^2\right)$ shows a concentration of events in the region 700 < M $(\pi^+\pi^-)$ < 800 MeV. This phenomenon in not observed for the events giving the $(K\bar{K}\pi)^o$ mass either just below or above the 1290 MeV region.

Accordingly, this suggests that the dominant process here is

$$\bar{p}p \rightarrow D^o\rho^o \qquad \text{20 events.}$$

For reaction (3), where the ρ^o is forbidden, there is some indication for the process

$$\bar{p}p \rightarrow D^o\eta^o \qquad \text{8 events.}$$

To investigate the mode $\bar{p}p \to D^o\pi^o$, we have looked at the mass-spectrum of the neutral $(K\bar{K}\pi)$ system for reaction (6). No statistically significant enhancement is seen here in the D region. More precisely, the best estimate for this reaction is :

$$\bar{p}p \to D^o\pi^o \qquad\qquad 5 \text{ events.}$$

We conclude accordingly that the D^o is produced mainly via a two-body production mechanism. Furthermore, the production with the vector mesons appears stronger than with the pseudoscalar mesons. The production angular distributions are consistent with isotropy but because of limited statistics do not provide a strong test of the S-wave production.

A study of $\bar{p}p$ annihilations at rest gave no evidence for D-meson although the statistics were of the same order[2]. However it should be noted that $D\rho$ and $D\omega$ channals are energetically forbidden at rest. Furthermore, if the I-spin of the D meson is zero, and we assume S-wave capture[3], then $\bar{p}p \to D\rho$ and $\bar{p}p \to D\pi^o$ are also forbidden at rest for those assignments of quantum numbers for the D which seem the most likely (see below).

6) Assuming that the D corresponds to a well-defined state, we try next to indicate the set of quantum numbers I, G, J, P (denoted by I^G, J^P) in best agreement with our data.

For this study we have used a purified sample of D decays : more precisely, the events corresponding to $1.64 < M^2$ $(K^o_1 K^{\pm} \pi^{\mp}) < 1.72$ GeV^2 for reactions (1), (3) and (5), with the additional restriction, for reactions (1) and (5) that the D be produced in association with a ρ^o and an ω^o, respectively. In these conditions, the background does not represent more than 30 % of the sample.

Fig. 3 shows no clear evidence for a $(K\pi)$ or a $(K\bar{K})$ resonance : in particular, neither the K (725) nor the possible $K\bar{K}$ states (1025 and 1250)[4]. However, we connot exclude the presence of the tail of K (890) or strong $(K\bar{K})$ interaction. For the moment, we shall assume that the population of the decay Dalitz-plot (fig. 4) is governed by the properties of the decay matrix element as determined mainly by its transformation properties rather than final state interactions.

Furthermore, we assume the D meson decays via strong interactions : this hypothesis is supported by our experimental results which seem to indicate that the natural width of the D-meson is not zero.

Let us represent the $(K\bar{K}\pi)$ system by a $(K\bar{K})$ sub-system with an orbital angular momentum L with respect to the pion. Let us denote by $I_{(K\bar{K})}$, $\ell_{(K\bar{K})}$ and $G_{(K\bar{K})}$ the isospin, angular momentum and G-parity of the $(K\bar{K})$ sub-system.

G-parity

Since we are dealing here with the $\bar{K^o} K^+$ and $K^o K^-$ systems, we have $I_{(K\bar{K})} = 1$. Furthermore, the non-vanishing of population density at the low mass end of the $K\bar{K}$ spectrum leads us to believe that $\ell_{(K\bar{K})} = 0$ is dominant. Then,

$$G_{(K\bar{K})} = (-1)^{I_{K\bar{K}} + \ell_{K\bar{K}}} = -1$$

$$\text{and} \quad G_D = G_{(K\bar{K})} \cdot G_{\pi} = +1$$

I-spin

The presence of the reaction $\bar{p}p \to D^o\omega^o$ excludes the possibility I = 2. The non-observation of charged D, however, does not necessarily forbid I = 1, so that we are left with the two possibilities, I = 0, and I = 1. Since $C = G\,(-1)^I$ for a neutral system, the completely neutral decay mode of D^o can in principle provide the information on the I-spin. Furthermore, the observation of the reaction $\bar{p}p \to D^o\rho^o$ allows us to predict a minimum number of events of the type $\bar{p}p \to D^{\pm}\,\rho^{\mp}$ that must be observed if I = 1. Accepting the previous determination of G parity and using the fact that we observe ~ 25 examples of $D^o \to K_1^o\, K^{\pm}\, \pi^{\mp}$ in reaction (1), of which ~ 18 are produced in association with the ρ, the expected(*) and observed number of events for each hypothesis is shown in table I.

TABLE I - No. of events expected and observed

<table>
<tr><th></th><th>Expected for I = 0</th><th>Expected for I = 1</th><th>Observed</th></tr>
<tr><td>Reaction (2) :
$D^o \to K_1^o K_1^o \pi^o$</td><td>$5 \pm 1$</td><td>0</td><td>$8 \pm 4$</td></tr>
<tr><td>Reaction (4) :
$D^o \to K_1^o K_1^o \pi^o$
$\quad \hookrightarrow \pi^o \pi^o$</td><td>$5 \pm 1$</td><td>0</td><td rowspan="2">7 ± 6</td></tr>
<tr><td>Reaction (4) :
$D^o \to K_1^o K_2^o \pi^o$</td><td>0</td><td>undetermined</td></tr>
<tr><td>Reaction (2) :
$\bar{p}p \to D^{\pm} \rho^{\mp}$
$\rho^{\mp} \to K_1^o K_1^o \pi^{\mp}$</td><td>0</td><td>$> 7 \pm 2$</td><td>$0 \pm 3$</td></tr>
</table>

Although the data favor I = 0 hypothesis a rigourous exclusion of I = 1 is impossible.

Spin-parity

Still using the above hypothesis $\ell_{(K\bar{K})} = 0$, the spin J and parity P of the D-meson are given by :

$$J = L$$
$$P = (-1)^{L+1}$$

Under the assumption of no final state strong interaction the kinetic energy spectrum of the pion, divided by phase space factor should be flat for L = 0 and follow p_π^2 and p_π^4 laws for L = 1 and L = 2, respectively. The data are inconsistent with the L = 0 hypothesis, but cannot discriminate between L = 1 and L = 2(**). Thus the most logical assignments for the D meson, if we limit oursalves to $J \leq 2$, seem to be $J^P = 1^+$ and 2^-.

Howener, if we interpret the observed population density in the Dalitz-plot as being due to a strong S-wave interaction between the 2 K mesons, then 0^- assignement for the D-meson is also consistent with the data.

The decay distribution of the $(K\bar{K})$ sub-system with respect to the pion direction is isotropic, in agreement with all of these possibilities.

This set of quantum numbers forbid the decay mode $D \to K\bar{K}$; an investigation of the $K\bar{K}$ mass spectra for the reactions $\bar{p}p \to K\bar{K}n\pi$ shows no enhancement in the region of the D-meson.

7) We conclude that we observe a resonant state D decaying into $K\bar{K}$ with a mass of 1290 MeV and a width $\Gamma \sim 25$ MeV.

On the assumption that the decay observed is a strong decay, the best quantum number assignments seem to be $I^G = 0^+$ or 1^+, with the former slightly favoured, and $J^P = 1^+$ or 2^-, with 0^- not completely excluded. These conclusions are in agreement with those reached by D. Miller et al.(1).

If these assignments are correct, then for $I^G = 0^+$, $\eta\pi\pi$ and 4π should be the simplest competing decay modes, whereas for $I^G = 1^+$, $\omega\pi$ should also compete favourably.

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Furthermore, we would like to acknowledge with thanks the help of our collegues H. Davis, F. James, F. Bruyant, and J. Zoll.

REFERENCES

1) During the writing of the final draft of this paper we have received a preprint from Prof. D. Miller discussing the observation of this state in $\pi^- p$ interactions and suggesting for it the name D meson (D.H. Miller et al., submitted to Physical Review Letters).

2) R. Armenteros et al., reported at the International Conference on High-Energy Physics, Dubna, USSR, 1964 (in press). See also Proceedings of the Siena International Conference on Elementary Particles, 1963 (Societa Italiana di Fisica, Bologna, Italy, 1963).

3) That this is indeed the case for the reaction $\bar{p}p \to K^o \bar{K}^o$ has been verified experimentally by R. Armenteros et al., 1962 International Conference on High Energy Physics, CERN, Geneva, p.351.

4) R. Armenteros et al., submitted to Physics Letters.

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(*) The production ratio $R = \bar{p}p \to D^{\pm}\rho^{\mp}/\bar{p}p \to D^o\rho^o$ must satisfy the requirement $R \geq 2$. However for I = 1, C = - 1 hypothesis our detection efficiency is 6 times higher for the process $\bar{p}p \to D^o\rho^o$, $D^o \to K_1^o K^{\pm} \pi^{\mp}$ than for $\bar{p}p \to D^{\pm}\rho^{\mp}$. Thus experimentally we must have $R \geq \frac{1}{3}$. For I = 0, C = + 1 hypothesis, the expected ratio for $D^o \to K_1^o K_1^o \pi^o / D^o \to K_1^o K^{\pm} \pi^{\mp}$, after taking into account the detection efficiency for K_1^o, is 1/6. This ratio is undetermined for the I = 1, C = - 1 hypothesis because of the presence of 2 independent amplitudes in the D decay under this assumption, i.e. $I_{K\bar{K}} = 0$ and $I_{K\bar{K}} = 1$. In quoting the number of expected events we have taken into account the fact that corrections for ambiguous and unmeasurable events are slightly different for reaction (2) than for reaction (1).

(**) The discrimination between these 2 possibilities is furthermore complicated by the fact that for $J^P = 2^-$ we can also have $\ell = 2$, L = 0 component. A small contribution due to this component is not excluded by the data.

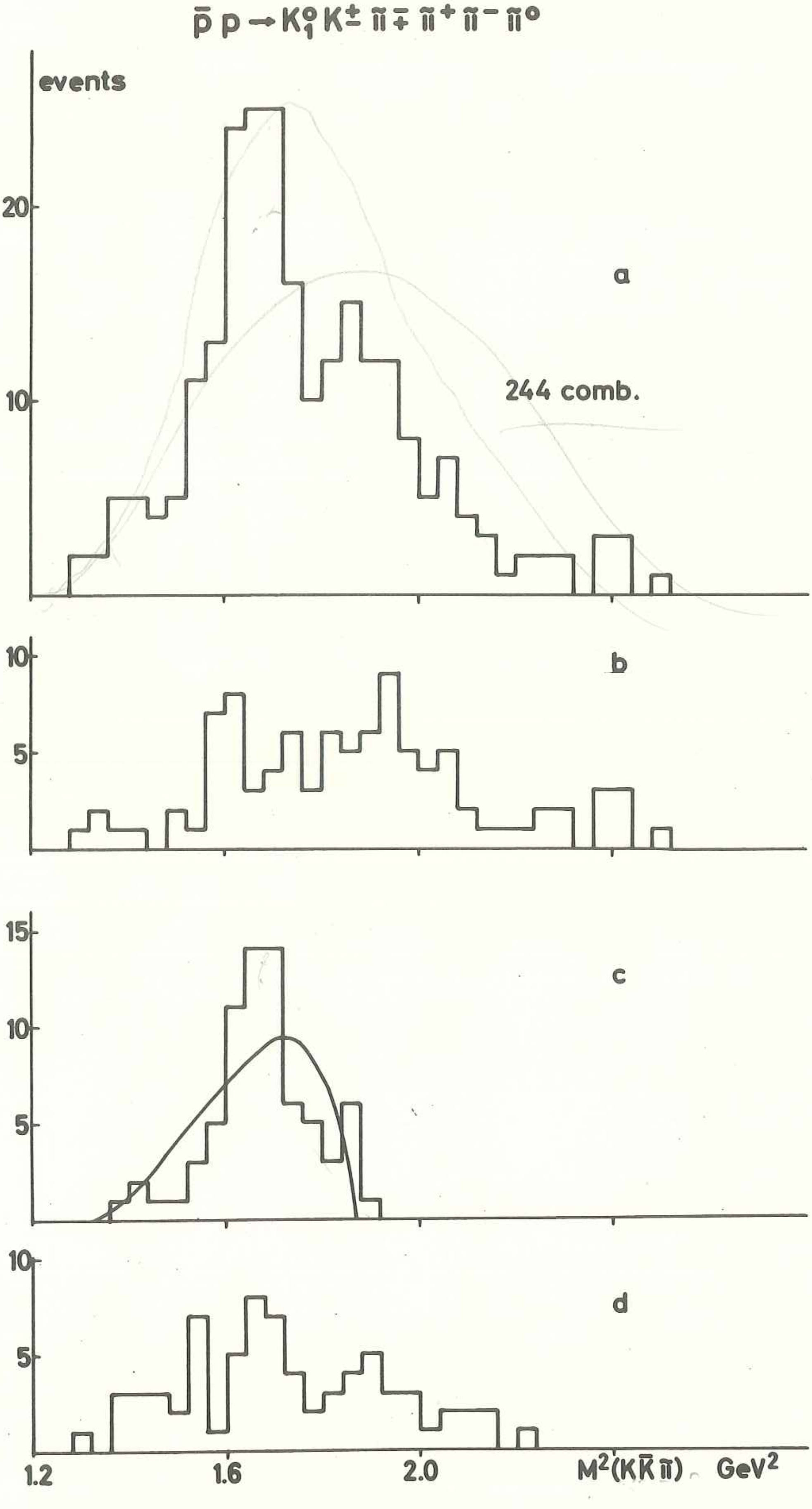

Fig. 2

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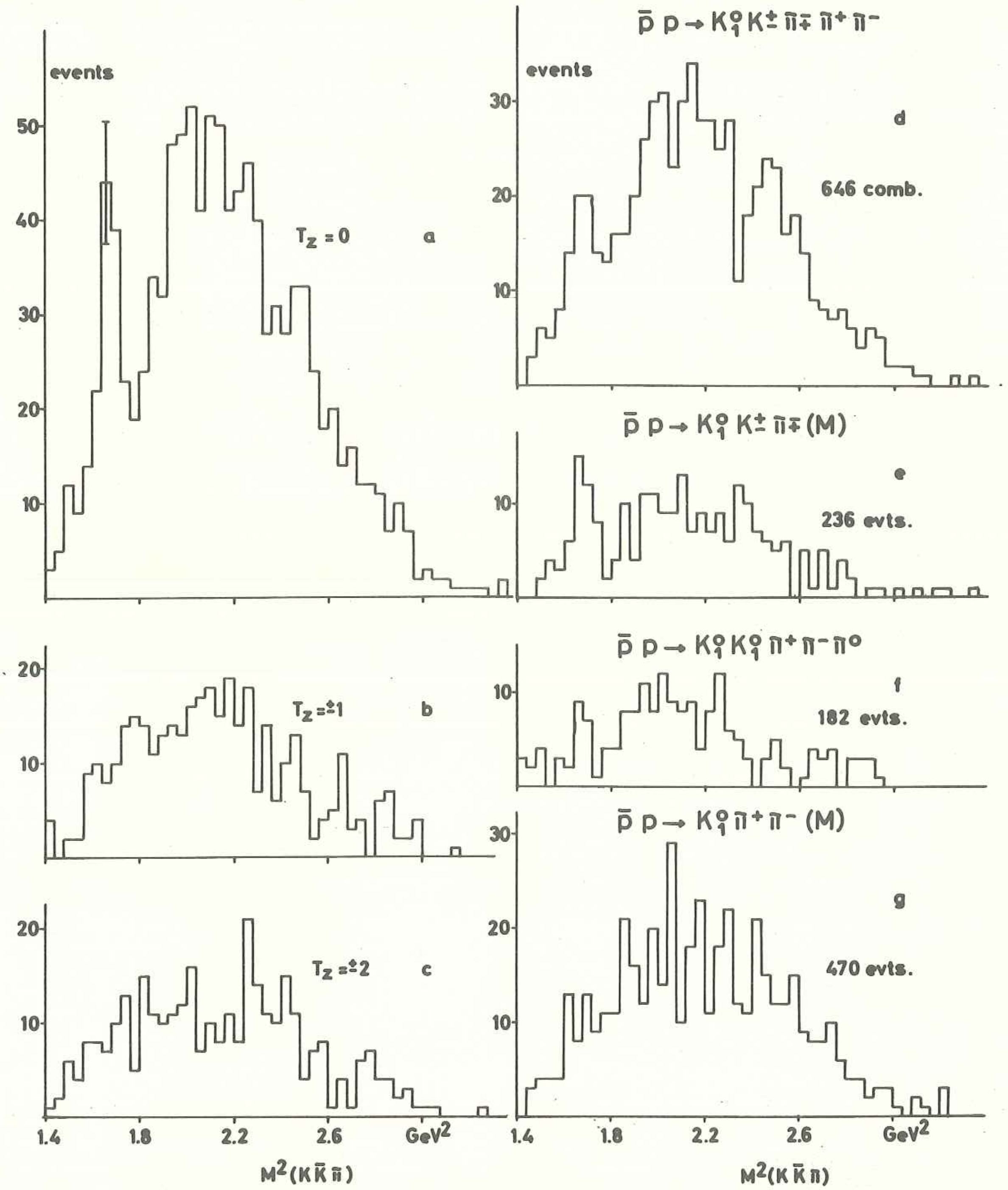

Fig. 1

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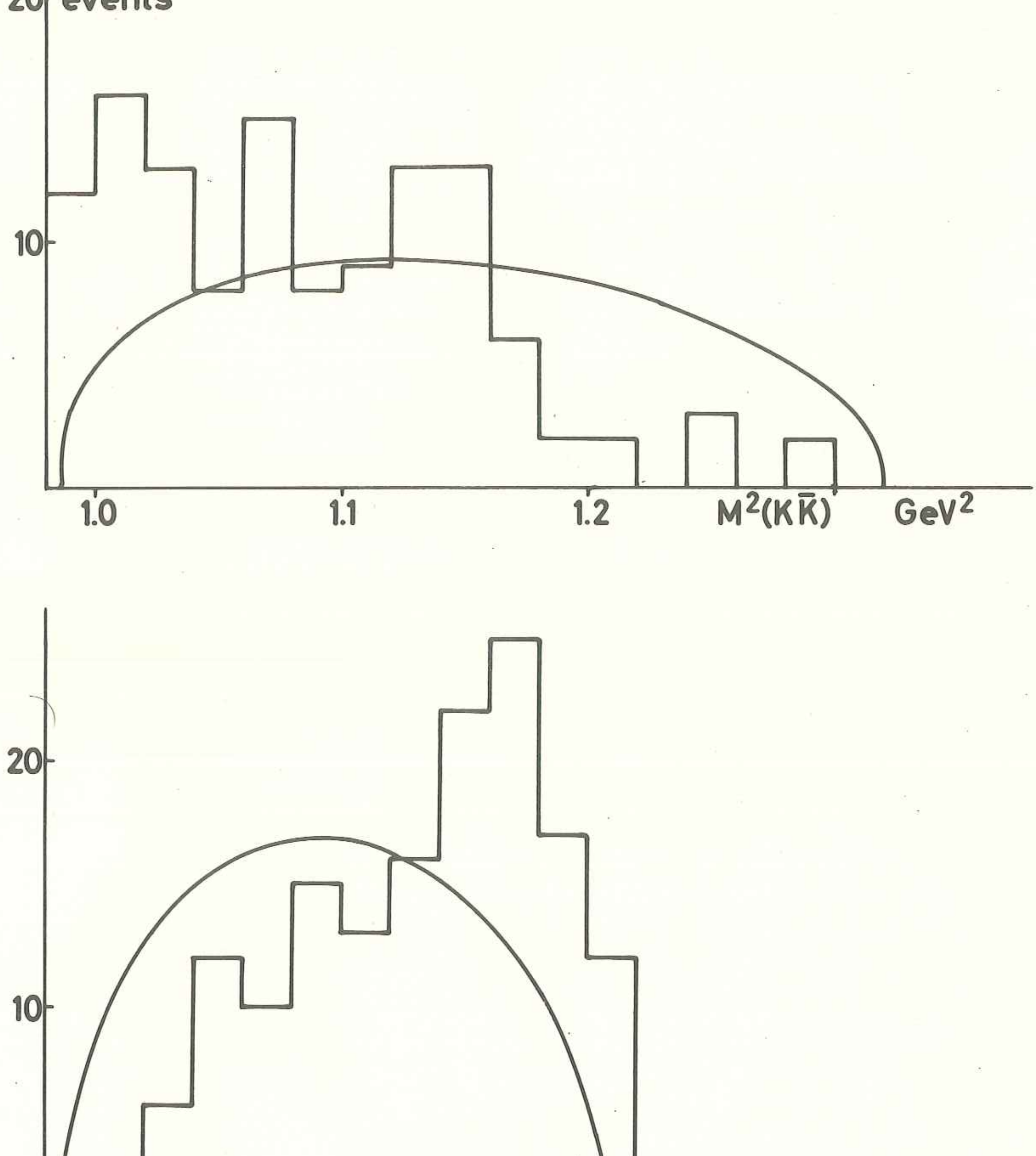

Fig. 3

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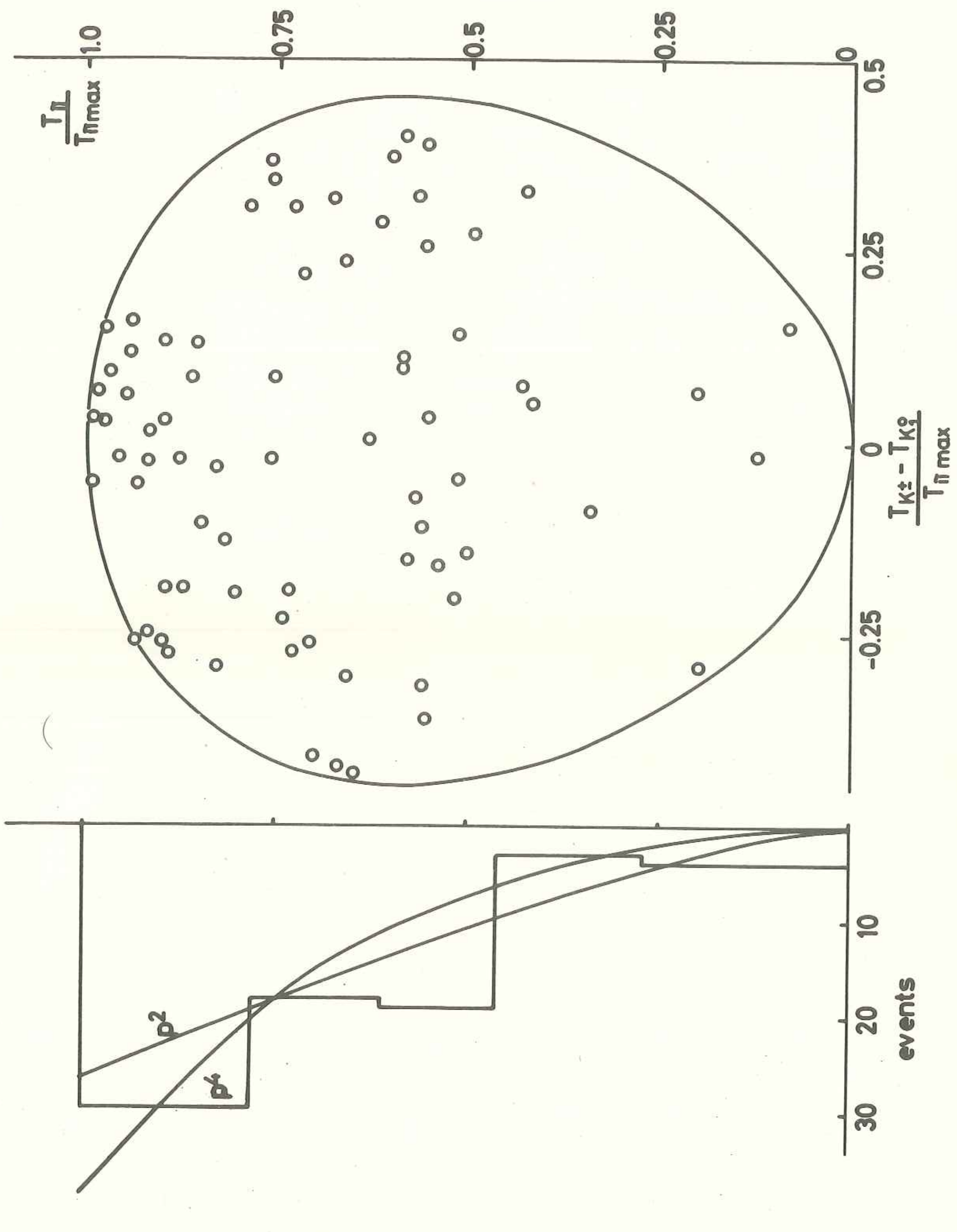

Fig. 4

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FIGURE LEGENDS

Fig. 1 - (a), (b), and (c) - Effective mass squared spectra for the neutral, singly, and doubly charged $K\bar{K}\pi$ systems, respectively, available from reactions (1), (2), and (3).

(d), (e), and (f) - Effective mass squared spectra for the neutral $K\bar{K}\pi$ systems from reactions (1), (2), and (3) respectively.

(g) - Missing mass squared spectrum for the K_1^oM system for reaction (4).

Fig. 2 - Effective mass squared spectra of the neutral $K\bar{K}\pi$ combinations from the reaction $\bar{p}p \rightarrow K_1^oK^{\pm}\pi^{\mp}\pi^+\pi^-\pi^o$.

(a) Both combinations for all the events.

(b) Both combinations for non-ω events.

(c) Combination recoiling against the ω, for ω events. The phase space curve is normalized to all the events.

(d) That combination for the ω events which includes the pion which also forms the ω.

Fig. 3 - Effective mass squared spectra of the $K\bar{K}$ and $K\pi$ systems for the events in the D region. The curves are phase space predictions.

Fig. 4 - Dalitz plot for the events in the D band ($1.64 < M^2(K_1^oK^{\pm}\pi^{\mp}) < 1.72$ GeV^2). All kinetic energies are evaluated in the $KK\pi$ rest frome. The contour to a high degree of accuracy independent of the mass of the $KK\pi$ system. The contour, to a high degree of accuracy independent of the mass of the $K\bar{K}\pi$ system, has been evaluated for $M(K\bar{K}\pi) = 1290$ MeV.