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The recent work at Berkeley[1] on π^-p interactions has given evidence for the existence of an excited state in the $K\pi$ system at ~725 MeV which the authors chose to call the κ meson. To search for this effect in K^-p interactions we have undertaken a systematic analysis of the reaction

$$K^- + p \rightarrow \overline{K}^0 + \pi^- + p \qquad (1)$$

over the range of momenta from 1.0 to 1.7 GeV/c. We find a significant enhancement centered at 723 ± 3 MeV, with a width less than 12 MeV. We cannot rule out the possibility that the observed width is due entirely to the experimental resolution. Because of insufficient statistics we are unable to draw any conclusions as to the spin or parity of this resonance. Some theoretical implications of the κ are considered.

The exposure was taken in the Lawrence Radiation Laboratory's 72-inch hydrogen bubble chamber, in the separated K^- beam designed under the direction of H. K. Ticho.[2] The amount of film taken and the number of events obtained at each momentum setting are summarized in Table I. The path length was obtained by (a) counting the number of τ decays and (b) normalizing the total number of interactions to the known total cross sections.[3] The two methods agreed to within 10% at each momentum. The typical spread in the momentum of the beam at each setting was of the order of ±3%.

In the study we used two-prong events with an associated V^0, i.e. $\overline{K}^0$ decaying via the charged K_1^0 mode. The events were processed through our track reconstruction and kinematical fitting program PACKAGE. In about 98% of the cases, examples of reaction (1) were separated unambiguously from other reactions possessing the same topology. The ambiguous events could always be resolved by inspection of the ionization of the two positive tracks. The number of events obtained at each momentum is given in Table I.

The combined mass spectrum of the $\overline{K}^0\pi^-$ system for all momenta in this experiment is shown in Fig. 1a. It is clear that the 890-MeV K^* dominates reaction (1) at all momenta. Inspection of the Dalitz plots (not shown) indicates that neither the 1238-MeV N^* resonance nor the recently discovered 1660-MeV Y_1^* [4] appears to play a prominent role in the reaction. The curve drawn over the data represents the expected distribution if at all momenta the reaction proceeds 75% of the time via the mode

$$K^- + p \rightarrow \overline{K}^{*-}(890\ \text{MeV}) + p, \quad \overline{K}^{*-} \rightarrow \overline{K}^0 + \pi^- \tag{2}$$

and the other 25% of the time by the three-body mode (1). It appears that the curve reproduces the data quite well except in the region of 723 MeV, where a significant enhancement is observed (33 events above the background curve of 45). The bin size of 14 MeV in Fig. 1a was chosen to localize all of the effect in one bin. We henceforth limit ourselves to a discussion of the effect at 723 MeV.

We first turn to the question of the statistical significance of this enhancement. The $\overline{K}^0\pi^-$ mass region of interest (680 to 800 MeV) is displayed in Fig. 1b in 3-MeV intervals. The dashed curve represents a rough estimate of the background. The experimental resolution in this region of $\overline{K}^0\pi^-$ mass is approximately ± 3 MeV. We would not expect to see any real structure with a full width of less than 6 MeV. The data can be interpreted in one of two ways: either we see the effect of the kappa in the region from 719 to 731 MeV with a downward fluctuation near 727 MeV, or we see it from 719 to 725 MeV with an upward fluctuation near 730 MeV. The probability that the observed enhancement is due to a statistical accident is smaller than one chance in 10^6 for either interpretation of the data (if we assume that the dashed curve is the true representation of the background). If we raise the estimate of the background in this region to ~10 events/3-MeV interval (which appears to be incompatible with the data) the odds increase to one part in 10^4. In quoting these odds, we have taken the point of view that the region near 725 MeV has been specified by the π^- experiment. If we were to treat our experiment independently of the π^- data, we would have to multiply these odds by the number of bins in our spectrum (~30). We conclude that the enhancement near 725 MeV is statistically significant, even if no previous experiment had suggested evidence for a resonance in this region.

We now consider the properties of the kappa. In view of the low statistics and the various ways of interpreting the data we can at best estimate the central value[5] of the mass of the resonance to be 723 ± 3 MeV and the full width Γ to be less than 12 MeV. We cannot, however, exclude the possibility of a zero natural width. The fact that in no case does the κ have a measurable length sets an upper limit of $\approx 10^{-12}$ sec on the lifetime.

To investigate the effect of systematic errors (magnetic field, turbulence, etc.) on the mass of the $\overline{K}^0\pi^-$ system, we fitted the events giving a satisfactory χ^2 to reaction (1) to the hypothesis

$$K^- + p \rightarrow \pi_1^- + \pi_2^+ + \pi_3^+ + p, \qquad (3)$$

where the first two pions are the decay products of $\overline{K}^0$. Subsequently we calculated the mass of the (π_1^-, π_2^+) system. The results of this procedure for all examples of reaction (1) with $M(\overline{K}^0\pi^-) < 800$ MeV are illustrated in Fig. 2. In addition, we empirically tested the relative sensitivity of the mass of the $\overline{K}^0$ and the $\overline{K}^0$-π^- system to the various systematic errors. We have found that on the average the $\overline{K}^0$ mass is more sensitive than the $\overline{K}^0$-π^- mass by about a factor of 2 to various changes in the input data. This procedure gives us an upper limit of 1 MeV for possible systematic shifts in the κ mass, which is small compared with the statistical uncertainty. Furthermore, there should be no appreciable broadening of the mass distribution due to such systematic errors.

A rough estimate of the excitation function is given in Fig. 3. The number of κ's at each momentum was determined by plotting the $\bar{K}^0\pi^-$ masses in the 14-MeV bins of Fig. 1a and subtracting the average number of events in the two neighboring bins from the number in the central bin. The ordinate scale (μb) was obtained on the assumption of an $I = 1/2$ assignment for the κ. The scale should be doubled if the isotopic spin of the κ turns out to be 3/2. We assume that there is no appreciable rate of decay via electromagnetic transitions. Any systematic shifts in the κ mass as a function of K^- momentum are small compared to 14 MeV and would not influence this plot.

The $K\pi$ decay mode of the κ indicates a 0^+ or 1^- spin-parity assignment for this meson (for spin less than 2). We have examined the decay angular distributions of the κ and find that, within statistics, they are all compatible with isotropy. However, we feel that this fact should not be taken as evidence against the 1^- assignment because of the intrinsic difficulties associated with the relatively high background, low statistics, and wide range of incident momenta.

Assuming that the reaction

$$K^- + p \rightarrow \kappa^- + p \qquad (4)$$

proceeds via the one-pion exchange (OPE) diagram (as originally suggested for reaction (2) by Bég and De Celles[6]) one can relate the width of the κ to the cross section for reaction (4) for either a scalar (0^+) or vector (1^-) assignment for the κ. The data are insufficient to test to what extent the OPE diagram dominates the reaction. Assuming however that the OPE diagram is the dominant one, and that the I - spin of the κ is 1/2, we obtain a width of the order of 1 to 3 MeV for the scalar hypothesis, and about 10 to 100 keV for the vector assumption. Neither value is ruled out by the experiment. Furthermore, the OPE diagram yields a slight forward peaking of the angular distribution of the κ for the scalar hypothesis. Some enhancement in the forward direction is indeed observed, but it may be due to the background.

It would be of interest to ascertain whether the decay mode $\kappa^- \to K^- + \gamma$ exists, as its observation would rule out the 0^+ assignment. However, this decay mode is inaccessible in our experiment. We can determine only the upper limit on another decay mode $\kappa^- \to \overline{K}^0 + \pi^- + \gamma$ to be 6% of the $\overline{K}^0\pi^-$ mode.[7] We find that we are unable to draw any conclusions as to the spin or parity of the κ.[8]

It is interesting to consider some of the theoretical implications of the κ meson. The SU_3 unitary symmetry scheme proposed by Gell-Mann[9] and Ne'eman[10] has been used with considerable success recently in classifying the known mesons and baryons into multiplets.[11] It is important to note that no other known mesons could form a unitary multiplet with the κ meson. It will be interesting to see if such "unitary partners" exist. There are presently two possible assignments for the κ that do not require any "partners." Takeda has pointed out a theory of the weak interactions which is compatible with all presently known experimental data, but which allows the possibility of copious production of the intermediate vector bosons.[12] Also Nambu and Sakurai have considered the hypothesis that the K^* (890 MeV) mesons are coupled to strangeness-changing currents which are conserved "as exactly as possible."[13] This hypothesis suggests the existence of a $Y = \pm 1$, $T = 1/2$, $J = 0^+$ meson whose coupling to other strongly interacting particles vanishes in the limit of exact unitary summetry. Present experimental data do not allow us to draw any conclusions as to the assignment of the κ meson to any of these schemes. Any discussion of assignments at this stage must be considered to be purely speculative.

We wish to thank Professor Luis W. Alvarez for his encouragement and support in this experiment. We are indebted to the operators of the 72-inch bubble chamber and of the Bevatron, and to our scanning and measuring staff, without whose help this experiment would not have been possible.

Table I. Path lengths and numbers of events

Incident K^- momentum (GeV/c)	Number of $\overline{K}^0 p\pi^-$ observed	Path length (events/μb)
1.08	109	0.4
1.22	601	1.2
1.33	604	1.5
1.43	362	0.8
1.51	2212	5.2
1.7	408	0.7[a]

[a] This number corresponds to the path length in which the reaction $K^- p \rightarrow \overline{K}^0 \pi^- p$ was analyzed. The total path length here is about 1.1 events/μb.

FOOTNOTES AND REFERENCES

* This work was done under the auspices of the U. S. Atomic Energy Commission.

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2. H. K. Ticho, G. Kalbfleisch, J. Kirz, D. Miller, J. B. Shafer, D. Stork, and C. Wohl, Lawrence Radiation Laboratory, Berkeley (unpublished work).
3. V. Cook, B. Cork, T. F. Hoang, D. Keefe, L. T. Kerth, W. A. Wenzel, and T. F. Zipf, Phys. Rev. 123, 320 (1961).
4. L. W. Alvarez, M. H. Alston, M. Ferro-Luzzi, D. O. Huwe, G. R. Kalbfleisch, D. H. Miller, J. J. Murray, A. H. Rosenfeld, J. B. Shafer, F. T. Solmitz, and S. G. Wojcicki, Phys. Rev. Letters 10, 184 (1963).
5. The usual formula for the error on the central value is $\delta M = \sigma/\sqrt{N}$, where σ is the width of the distribution, either experimental or natural or both, and N the number of events in the sample. In this formula it is assumed that we can determine which events belong to the distribution under consideration. This is not true in the case of a resonance superimposed upon a high background. An additional uncertainty due to this background is introduced which is not taken into account in the above formula.
6. M. Baqi Bég and P. De Celles, Phys. Rev. Letters 6, 145, 428 (E) (1961); see also C. Chan, Phys. Rev. Letters 6, 383 (1961) and W. G. Wagner and D. H. Sharp, Phys. Rev. 128, 2899 (1962).

7. We observe no events which fit the hypothesis $K^- + p \to \bar{K}^0\pi^-\gamma p$ with the energy of the γ ray > 50 MeV, and the mass of the $\bar{K}^0\pi^-\gamma$ system in the κ mass band. If we assume that the energy spectrum of the γ rays is determined purely by phase-space considerations, the observation of one such event would give an upper limit of 6% for the branching ratio.

8. The strong decay of K^* (890 MeV) $\to \kappa + \pi$ is forbidden for a 0^+ kappa. As indicated by S. Glashow, (private communication), the ratio $R = \text{rate}\,(K^* \to \kappa + \pi)/\text{rate}\,(K^* \to K + \pi)$ can be calculated for a 1^- assignment (similar to that done by A. Rosenfeld, D. Carmony, and R. Van de Walle, Phys. Rev. Letters 8, 293 (1962) for $\rho \to \eta + \pi$). We obtain

$$R \sim 2(f/g)^2\,(q/p)^3,$$

where q and p are the decay momenta of κ and K, and f and g are coupling constants for K^* to $\kappa\pi$ and $K\pi$, respectively, and the factor of two arises from spin considerations. For f of the order of g, R is greater than 1%. An experimental value of R less than 0.1%, say, would suggest a 0^+ kappa. A preliminary value of R can be obtained from the reactions $K^- + p \to \bar{K}^0\pi^- p\pi^0$ and $K^-\pi^-\pi^+ p$ at 1.22 BeV/c. We have no $\bar{K}^0\pi^- p\pi^0$ events and 6 $K^-\pi^-\pi^+ p$ events which might be interpreted as $K^{*-} \to \kappa^0 + \pi$ and ~1300 K^{*-}, giving $R < 1\%$. We can draw no conclusions at this time.

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10. Y. Ne'eman, Nucl. Phys. 26, 222 (1961).

11. For a review of the experimental situation see reference 4 and S. L. Glashow and A. H. Rosenfeld, Phys. Rev. Letters 10, 192 (1963).

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13. Y. Nambu and J. J. Sakurai, K^* (725) and the Strangeness-Changing Currents of Unitary Symmetry, Enrico Fermi Institute for Nuclear Studies and the Department of Physics, University of Chicago, private communication; see the following paper.

FIGURE LEGENDS

Fig. 1. (a) Plot of the $\overline{K}^0\pi^-$ mass of the 4296 events from the reaction $K^-+p \rightarrow \overline{K}^0 \pi^- p$ at 1.0-1.7 BeV/c in 14-MeV intervals. The curve represents the phase space for the reaction proceeding 75% of the time through $K^-p \rightarrow \overline{K}^{*-}p$ and 25% through $K^-p \rightarrow \overline{K}^0 \pi^- p$ directly. The K^* mass is taken as 890 MeV, and its width Γ as 50 MeV. An enhancement is seen at 723 MeV of 33 events above the background curve of 45 (or 42 events above the average of the two neighboring bins).

(b) Plot of the 680 to 800-MeV mass region in 3-MeV intervals to show the structure of the distribution around the κ mass. The dashed curve represents a rough estimate of the background. The resolution is 6 MeV in this region.

Fig. 2. Plot of the $\overline{K}^0$ mass at each incident momentum as determined by fitting the $K^-p \rightarrow \overline{K}^0\pi^-p$ events as $K^-p \rightarrow (\pi_1^-, \pi_2^+) \pi^-p$ [i.e., without constraining the (π_1^-, π_2^+) to be a $\overline{K}^0$]. All events having a satisfactory χ^2 for the reaction $K^-p \rightarrow \overline{K}^0 \pi^-p$ and having a $\overline{K}^0\pi^-$ mass below 800 MeV were used. The average mass of the (π_1^-, π_2^+) from the fit is plotted as the ordinate.

Fig. 3. Excitation function for the reaction $K^- + p \rightarrow \kappa^- + p$ from 1.0 to 1.7 BeV/c. The cross sections were determined under the assumption that the κ has isotopic spin $I = 1/2$ and that the rate of decay via electromagnetic transitions is negligible. If the isotopic spin of the κ turns out to be $I = 3/2$, then the ordinate scale should be doubled.

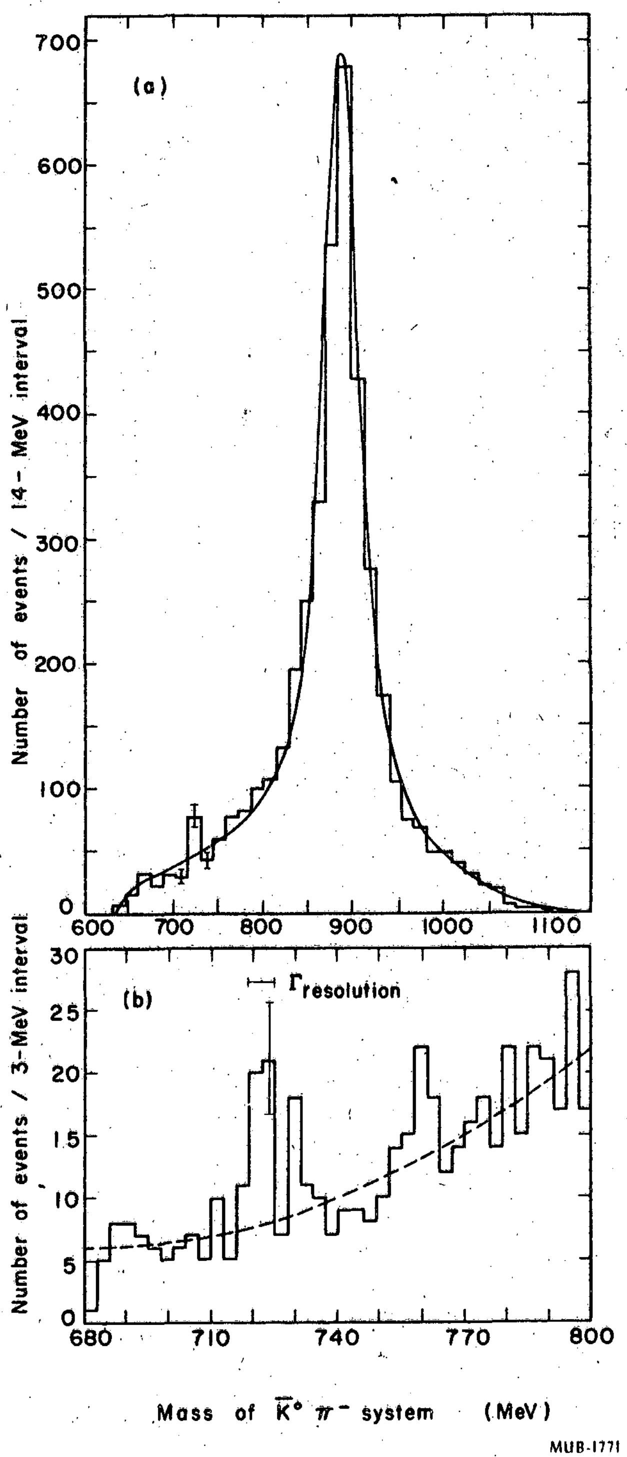

(a)
(b)
$\Gamma_{resolution}$
Number of events / 14- MeV interval
Number of events / 3-MeV interval
700
600
500
400
300
200
100
0
600
700
800
900
1000
1100
30
25
20
15
10
5
0
680
710
740
770
800
Mass of $\overline{K}^{\circ}\pi^{-}$ system (MeV)
MUB-1771

Fig. 1.

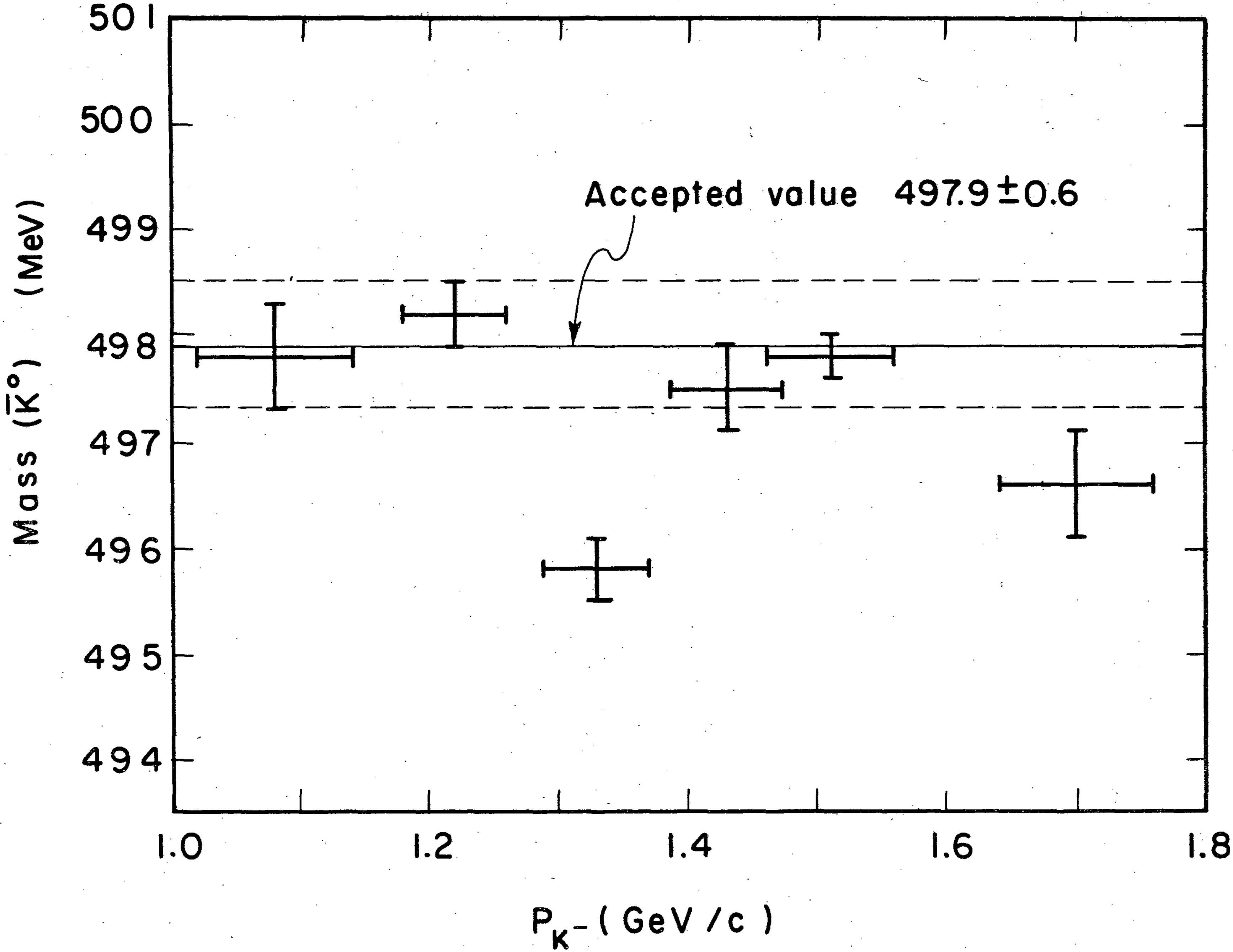
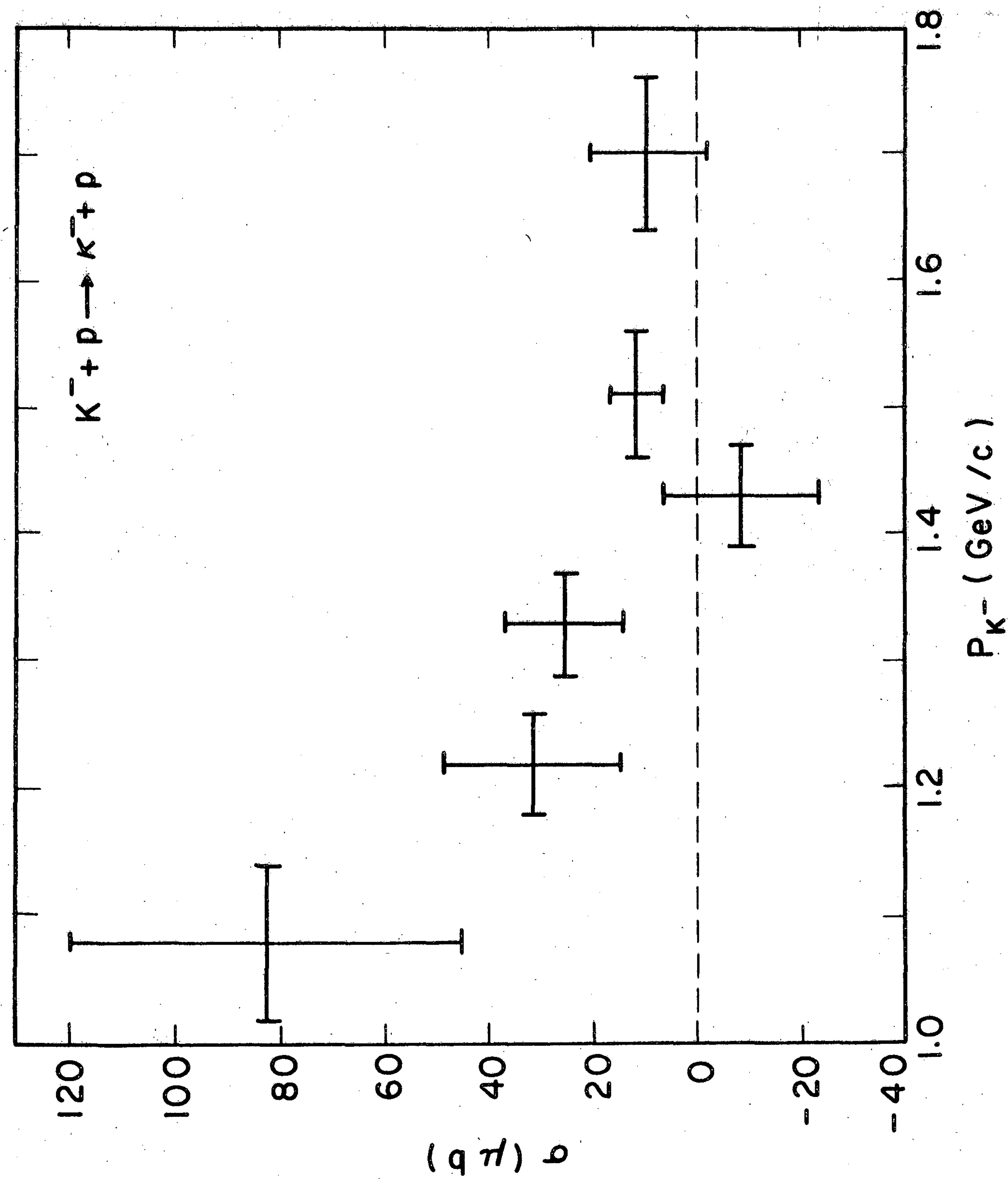


Fig. 2.

MU-30080



MU-30083

Fig. 3.