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LOW-MASS $K\bar{K}$ SYSTEMS PRODUCED IN π^-p INTERACTIONS BELOW 5 BeV/c*

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In a study of $K\bar{K}$ pairs produced in π^-p interactions from 1.5 to 4.2 BeV/c, we observe the $K_1^0 K_1^0$ threshold enhancement at all beam momenta, and the ϕ meson at beam momenta below 2.3 BeV/c. There are no significant enhancements in the K^0K^- system near threshold.

Recent studies have suggested the existence of several low-mass $K\bar{K}$ enhancements: (a) a threshold effect in the $K_1^0K_1^0$ system attributed to a large $I = 0$ scattering length;[1,2] (b) a $K_1^0K_1^0$ peak near $M = 1060$ MeV with full-width $\Gamma \simeq 80$ MeV interpreted as evidence for an $I = 0$ resonant state;[3,4] and (c) a narrow peak in the $K_1^0K^{\pm}$ system at $M \simeq 1025$ MeV with $\Gamma \simeq 40$ MeV, interpreted as an $I = 1$ resonance.[5,6] In addition, the low-mass $K_1^0K_2^0$ and K^+K^- final states exhibit peaks from decay of the well-established $I^GJ^P = 0^-1^-$ ϕ meson at 1020 MeV. In this letter we discuss the behavior of the $K\bar{K}$ systems observed in the reaction $\pi^-p \rightarrow K\bar{K}N$ below 5 BeV/c. Both the low-mass $K_1^0K_1^0$ threshold enhancement and the ϕ meson are observed in the $I = 0$ final states; no significant deviations from phase space are apparent in the $I = 1$ states at low effective mass.

The film was obtained using the Lawrence Radiation Laboratory's 72-in. hydrogen bubble chamber in the course of a systematic study of π^-p interactions within the interval 1.5 to 4.2 BeV/c. The experimental details have been discussed by Hess.[7] The observed numbers of events and corresponding cross sections are given in Table I.

A. $K_1^0K_1^0$ Threshold Enhancement

The $M(K_1^0K_1^0)$ distribution is shown in Fig. 1a for events with $\Delta^2(n) \leq 0.5$ $(\text{BeV}/c)^2$. The $\Delta^2(n)$ distribution in Fig. 1b demonstrates that this selection includes most events with $M(K_1^0K_1^0) \leq 1.075$ BeV. The strong peripheral production in this mass interval suggests production through pion exchange. In this case, the isotopic spin is zero for the initial $\pi\pi$ system since C is +1 for the $K_1^0K_1^0$ system. A quantitative test of the isotopic spin may be made with the charge-independence triangle inequality. For $I=1$ in the observed $K_1^0K_1^0$ system, we have

$$\{2\sigma[\pi^- p \rightarrow (K\bar{K})^0 n]\}^{1/2} \leq \{\sigma[\pi^+ p \rightarrow (K\bar{K})^+ p]\}^{1/2} + \{\sigma[\pi^- p \rightarrow (K\bar{K})^- p]\}^{1/2}. \quad (1)$$

If we use the data of Lander et al.[8] for $\pi^+ p \rightarrow (K\bar{K})^+ p$ at 3.5 BeV/c and our data at 3.2 BeV/c, (1) becomes

$$(60 \pm 20)^{1/2} \leq (6.0 \pm 6.0)^{1/2} + (1.4 \pm 1.4)^{1/2}, \quad (2)$$

where the values are given in microbarns. Since the inequality is poorly satisfied, we conclude that $I = 0$ for the low-mass $K_1^0K_1^0$ system. The distributions in decay angle and Treiman-Yang angle are shown in Figs. 1c and 1d for all events with $M(K_1^0K_1^0) \leq 1.075$ BeV; they are consistent with the isotropic distributions expected for a $J^P = 0^+$ state.

In experiments above 5 BeV/c[3,4] the same reaction yields a peak in the $K_1^0K_1^0$ mass distribution near 1060 MeV, with $\Gamma \approx 80$ MeV, suggesting a resonant state. The dashed curve in Fig. 1a, representing phase space multiplied by a Breit-Wigner resonance, is in poor agreement with the present data; the enhancement is more naturally interpreted as the manifestation of a large scattering length in the $I = 0$ $K\bar{K}$ system. For quantitative comparison we have used the Chew-Low formula[9] modified by the Selleri form-factor.[10] If we use the zero-effective-range approximation[11] and detailed balancing, the $I = 0$ S-wave $K\bar{K}$ production cross section is given by

$$\sigma_0(\pi\pi \rightarrow K\bar{K}) = \left(\frac{4\pi k_K}{k_\pi^2}\right) 2b_0 [(1+b_0k_K)^2 + (a_0k_K)^2]^{-1}, \quad (3)$$

where $A_0 = a_0 + ib_0$ is the S-wave $K\bar{K}$ scattering length, and $k_\pi(k_K)$ is the momentum of either pion (or K meson) in the $\pi\pi$ c.m. system. Then we have

$$\sigma(\pi^-\pi^+ \to K_1^0 K_1^0) = \left(\frac{1}{3}\right)\left(\frac{1}{4}\right) \sigma_0 (\pi\pi \to K\bar{K}). \tag{4}$$

The data are reasonably well-fitted[12] with a_0 between 2 and 6 F, if $b_0 \simeq 0.6\, a_0 - 0.5\,\text{F}$. The calculated Δ^2 distribution using these parameters is shown in Fig. 1b.

B. ϕ Meson

Since the ϕ meson decays predominantly into $K_1^0 K_2^0$ and K^+K^-, we must study its production in the reaction $\pi^- p \to K^+K^- n$. For an event to be fitted to this final state, at least one of the charged Kaons must decay in the chamber; in addition, each track must be long enough for a reasonably accurate momentum measurement. Events fitting the K^+K^-n hypothesis were examined on the scan table for consistency of track ionization with calculated values. At low beam momenta (1.5 to 2.3 BeV/c) about 50% of the fits were rejected; at higher beam momenta about 40%. The effectiveness of the procedure decreased at higher momenta, since the tracks were more frequently near minimum ionization. It is estimated that the contamination in low-momentum events finally accepted is less than 10%; the contamination could be as high as 50% near 4.2 BeV/c.

The distribution in $M(K^+K^-)$ is shown in Fig. 2a for events with beam momentum between 1.5 and 2.3 BeV/c. The striking feature of the data is the sharp peak at $M(K^+K^-) = 1021 \pm 4$ MeV with $\Gamma = 10 \pm 3$ MeV. When the experimental resolution of 5 MeV is unfolded, the values are consistent with those accepted for the ϕ meson, i.e., $M_\phi = 1019.5$ MeV and $\Gamma_\phi = 3.3$ MeV. The $\Delta^2(n)$ distribution in Fig. 2b for events with $M(K^+K^-)$ between 1005 and 1035 MeV differs markedly from the corresponding distribution for $K_1^0K_1^0$ events, shown shaded in Fig. 1b. This provides further evidence that the K^+K^- peak has an origin different from the S-wave threshold enhancement.

In order to determine detection efficiencies, events corresponding to $\pi^-p \rightarrow \phi n$ were generated by using the Monte Carlo program FAKE.[13] Because of limited data, calculations are shown in Fig. 2b, 2c, and 2d only for isotropic production and decay distributions. Although the decay angular distribution is consistent with being isotropic, a better fit is obtained when linear and quadratic terms are included. The linear term may result from interference with background arising from the S-wave threshold enhancement. The curve in Fig. 2a represents 20% threshold enhancement estimated from the effect observed in the K_1K_1 final state and calculated detection efficiencies, 40% ϕ production, and 40% phase space. Production cross sections are given in Table II; they were calculated using the branching fraction $(\phi \rightarrow K^+K^-)/(\phi \rightarrow \text{all decays}) = 0.48 + 0.04$ determined by Lindsey and Smith.[14]

In the simplest model of ϕ production through ρ exchange, the decay angular distribution is proportional to $\sin^2\theta$. We do not observe this correlation, but absorptive effects can modify the distribution significantly.[15] However, it is interesting to note that the observed production and decay distributions are similar to those reported by Kraemer et al.[16] for $\pi^+n \rightarrow \omega p$. Cross sections for $\pi^+n \rightarrow \omega p$ and $\pi^-p \rightarrow \phi n$ may be related through SU_3 and charge symmetry (or any model involving ρ exchange). Available data[16,17,18,19] are compared in Fig. 3. The abscissa is the c.m. momentum for the final state; the energy dependencies correspond roughly when the ordinate for $\pi^- p \to \phi n$ in increased by ~50. Other experiments[20,21,22] suggest that the ratio of cross sections for $\pi^+ p \to \omega N^{*++}$ and $\pi^+ p \to \phi N^{*++}$ is ~70.

C. The I = 1 $K\bar{K}$ System

We searched in the reaction $\pi^- p \to K^- K^0 p$ for the $K^0 K^\pm$ state observed in $p\bar{p}$ annihilations.[5,6] Our data show no evidence for the production of such a state; the one-standard-deviation upper limit to its cross section is 1 μb (3 μb) at 2 BeV/c (3.2 BeV/c). This observation is consistent with the assumption that (a) most low mass $K\bar{K}$ systems are produced by π or ρ exchange, and (b) the low mass $K^0 K^\pm$ state has quantum numbers $I^G J^P = 1^- 0^+$. Should the charged $K\bar{K}$ enhancement reflect the existence of a bound state below threshold, decay into $\pi\eta$ is expected to dominate; this may correspond to the sharp peak observed by Kienzle et al.[23] and by Oostens et al.[24] at around 965 MeV.

We are indebted to the scanning, measuring, and programming staffs whose efforts made this work possible. The film was exposed in a beam designed collaboratively between the Goldhaber-Trilling and Alvarez groups. We thank especially Dr. John A. Kadyk, Dr. George H. Trilling, and Dr. Joseph J. Murray for their contributions. It is a pleasure to acknowledge the support and encouragement of Professor Luis Alvarez throughout the course of this experiment.

FOOTNOTES AND REFERENCES

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$$F(\Delta^2) = 0.72[1+(\Delta^2+M_\pi^2)(4.73\,M_\pi^2)^{-1}]^{-1} + 0.28,$$

the $K\bar{K}$ mass spectrum becomes

$$\frac{d\sigma}{dM} = \frac{f^2}{2\pi}\,\frac{2M^2k_K}{M_\pi^2 k_\pi P_\pi^2}\left[\int F(\Delta^2)\,\frac{\Delta^2 d\Delta^2}{(\Delta^2+M_\pi^2)^2}\right]\sigma(\pi\pi\to K\bar{K}),$$

where $f^2 = 0.16$. Although this form factor was not deduced for the reaction we consider, it should account qualitatively for deviations from the one-pion-exchange model. Our conclusions are not sensitive to the detailed form factor used.

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Table I. Cross sections for the observed final states.

Final state	Momentum interval (BeV/c)	Number of events[a]	Cross section (μb)
pK^0K^-	1.6 to 2.4	249	31.9 ± 3.5
	2.9 to 3.3	228	65.1 ± 5.3
	3.8 to 4.2	95	65.7 ± 7.9
$nK_1^0K_1^0$	1.6 to 2.4	157	15.8 ± 4.2
	2.9 to 3.3	201	45.3 ± 4.1
	3.8 to 4.2	68	36.6 ± 5.1
nK^+K^-	1.5 to 2.3	86	39 ± 10
	2.9 to 3.3	90	195 ± 60
	3.8 to 4.2	48	370 ± 130

a. The numbers of events in the final states pK^0K^- and $nK_1^0K_1^0$ include only those events where the $K_1^0 \rightarrow \pi^+\pi^-$ decays are seen in the chamber. The numbers of events in the nK^+K^- final state include only those events where a K^+ or K^- decay is seen in the chamber. The cross sections were corrected for those efficiencies.

Table II. Cross sections for production of the threshold enhancement and the ϕ meson.

Process	Momentum (BeV/c)	Cross section (μb)
$\pi^- p \to n + (T.E.)$ [a]	1.8 to 2.2	7.9 ± 2.0
$(T.E.) \to K_1^0 K_1^0$	2.9 to 3.3	7.5 ± 2.5
	3.8 to 4.2	9.0 ± 3.7
$\pi^- p \to n\phi$	1.58 to 1.71	29.0 ± 15.0
	1.8 to 2.2	30.0 ± 8.0
	2.58 to 2.63	0.0 ± 9.0
	2.9 to 3.3	6.0 ± 8.0
	3.8 to 4.2	15.0 ± 20.0

a. T. E. Stands for threshold enhancement. The reported cross sections have been corrected for the unobserved K_1^0 decays only.

FIGURE LEGENDS

Fig. 1. Data from $nK_1{}^0K_1{}^0$ final states at all beam momenta. The events shown have been weighted for the detection efficiency of the $K_1 \rightarrow \pi^+\pi^-$ decay. The average weight is 1.3. Shaded events have a beam momentum less than 2.3 BeV/c. (a) $K_1{}^0K_1{}^0$ effective mass distribution. Curves compare the zero-effective-range approximation with a resonance shape having M = 1068 MeV and Γ = 80 MeV. (b) Distribution of $\Delta^2(n)$ for events with $M(K_1{}^0K_1{}^0) \leq 1075$ MeV. The curve is the prediction of one-pion exchange with the Selleri form factor. The structure in the curve results from combining data obtained at several beam momenta. (c) and (d) Histograms of the decay cosine ($= \hat{P}_K \cdot \hat{P}_{beam}$ in the $K\bar{K}$ system) and the Treiman-Yang angle for events with $M(K_1{}^0K_1{}^0) \leq 1075$ MeV. Two points have been plotted for each event.

Fig. 2. Data from nK^+K^- final states at beam momenta below 2.3 BeV/c. (a) K^+K^- effective-mass distribution. The curve is for 40% ϕ production, 40% phase space, and 20% threshold enhancement. (b), (c), and (d) Histograms of $\Delta^2(n)$, decay cosine, and Treiman-Yang angle for events with $1005 \leq M_{K^+K^-} \leq 1035$ MeV. Curves are Monte Carlo distributions for isotropic production and decay angular distributions.

Fig. 3. Total cross sections for $\pi^+ n \rightarrow p\omega$ from other experiments (solid symbols) and $\pi^- p \rightarrow n\phi$ from this experiment (open symbol). The abscissa is the c.m. momentum of the final-state particles. The ordinates differ by a factor of 50.

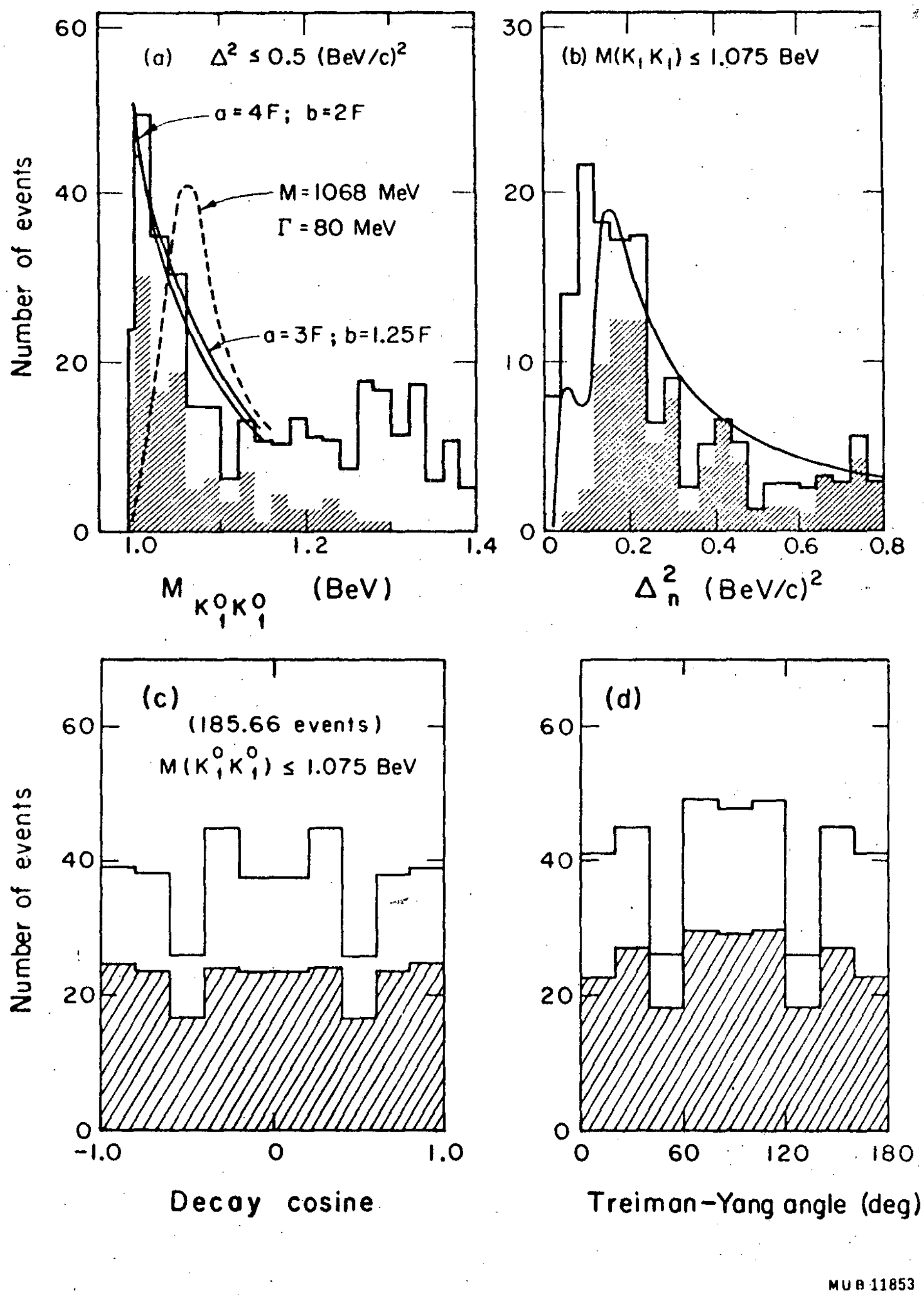
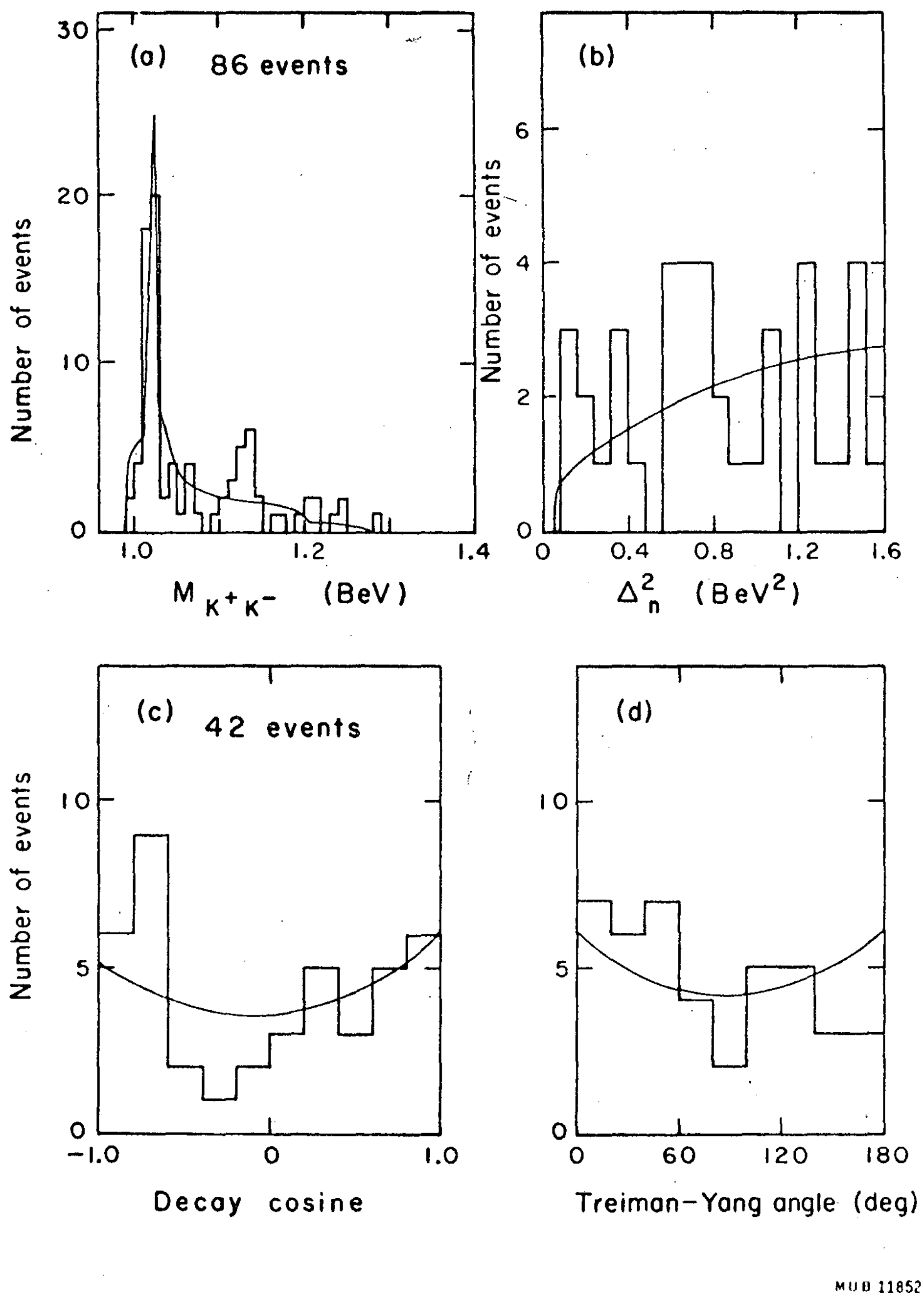

(a) Δ² ≤ 0.5 (BeV/c)²
a = 4F; b = 2F
M = 1068 MeV
Γ = 80 MeV
a = 3F ; b = 1.25F
Number of events
M K⁰₁K⁰₁ (BeV)
(b) M(K₁K₁) ≤ 1.075 BeV
Δ²ₙ (BeV/c)²
(c)
(185.66 events)
M(K⁰₁K⁰₁) ≤ 1.075 BeV
Number of events
Decay cosine
(d)
Treiman–Yang angle (deg)
MUB 11853

Fig. 1



(a) 86 events
Number of events
M K+K- (BeV)
(b)
Number of events
Δ²n (BeV²)
(c) 42 events
Number of events
Decay cosine
(d)
Treiman-Yang angle (deg)
MUB 11852

Fig. 2

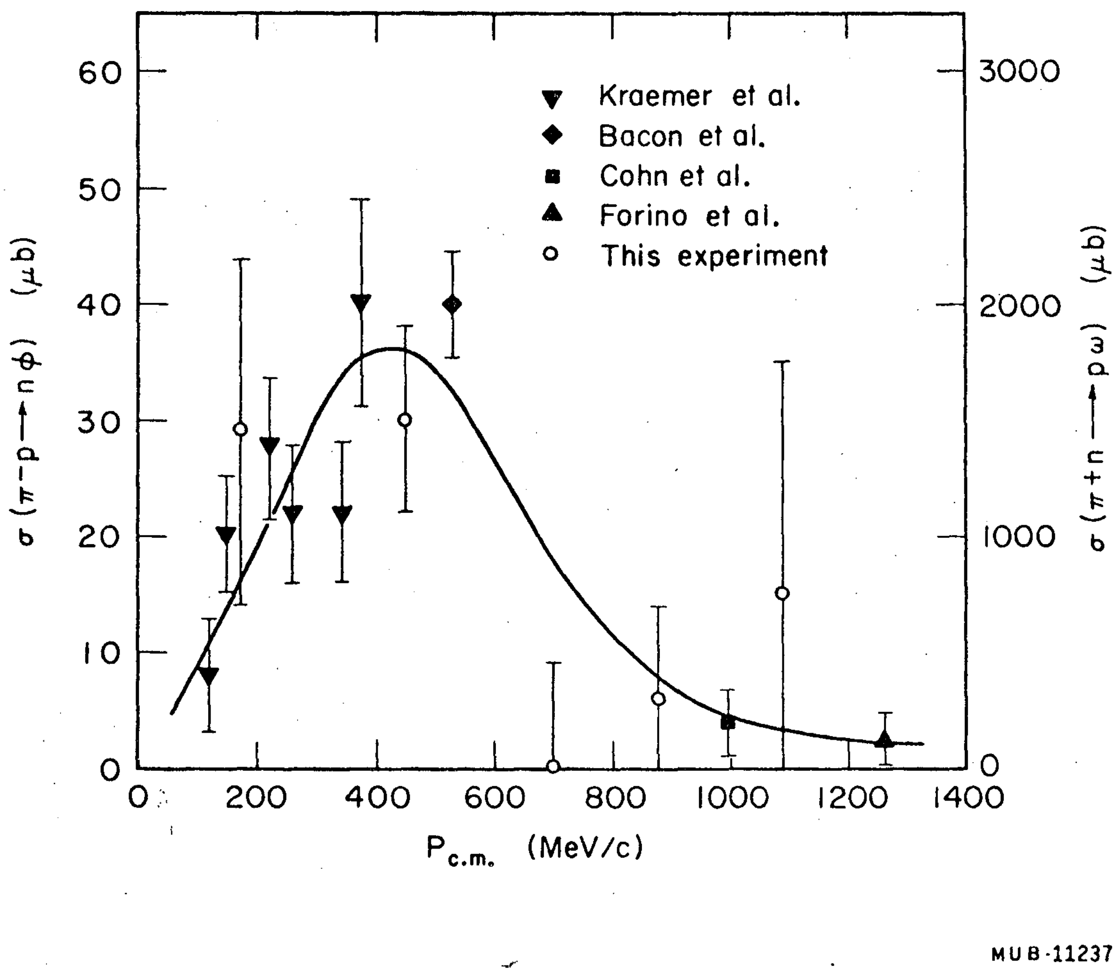

Kraemer et al.
Bacon et al.
Cohn et al.
Forino et al.
This experiment
σ (π−p ⟶ nφ) (μb)
σ (π+n ⟶ pω) (μb)
0
10
20
30
40
50
60
0
1000
2000
3000
0
200
400
600
800
1000
1200
1400
Pc.m. (MeV/c)
MUB-11237

Fig. 3