Measurement of the $T=\frac{3}{2}$ $K\pi$ Elastic Scattering Cross Section Using the Dürr-Pilkuhn Form Factor*

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We present a reanalysis of our original pole-extrapolation measurements of the $K^-\pi^-$ elastic scattering cross section for two intervals in $K\pi$ invariant mass from threshold to 0.84 GeV. These measurements were obtained from the reaction $K^-p \to K^-\pi^-\Delta^{++}$ at 2.05 and 2.63 GeV/c. We now show how the effect of the background from the competing one-pion-exchange process $K^-p \to (K^-\pi^+)(\pi^-p)$ can be approximately accounted for. We find that the extrapolated cross sections are relatively insensitive to the presence of this background. In addition we summarize some recent measurements of the $T=\frac{3}{2}$ $K\pi$ cross section.

We present a reanalysis of our earlier work,[1] in which we employed a Chew-Low[2] extrapolation to the pion pole, using the reaction

$$K^-p \to K^-\pi^-\Delta^{++} \tag{1}$$

in order to measure the $T=\frac{3}{2}$ $K\pi$ elastic scattering cross section. In our original study we noted the presence of a substantial background contribution from the competing reaction

$$K^-p \to K^{*0}(890)\pi^-p\ . \tag{2}$$

In this paper we calculate the background contribution explicitly, using a one-pion-exchange model for reaction (2), so that we may perform a background subtraction. Since the slopes of the extrapolations are thereby reduced, we obtain a more reliable value for the extrapolated $K\pi$ cross section. We also present a summary of other recent measurements, as well as the predictions of the Lovelace-Veneziano model[3] and current algebra.[4]

Events of the type $K^-p \to K^-p\pi^+\pi^-$ were obtained in exposures of the LRL 72-in. hydrogen bubble chamber to a separated K^- beam[5] with incident momenta in the range 2.0 to 2.7 GeV/c. The two samples selected for the $K\pi$ cross-section measurement consist of 7045 events[6] at 2.0 to 2.1 GeV/c (mean momentum = 2.05 GeV/c) and 9148 events at 2.51 to 2.78 GeV/c (mean momentum = 2.63 GeV/c). We use cross sections for the reaction $K^-p \to K^-\pi^-\pi^+p$ obtained by interpolating between values given by Dauber *et al.*[6] This reaction contains considerable amounts of both $\Delta^{++}(1238)$ and $K^{*0}(890)$, with lesser quantities of both $Y^{*0}(1520)$ and $\Delta^0(1238)$, the latter produced entirely with the $K^{*0}(890)$. Table I gives the amounts of these resonances produced in each event sample.

Under assumptions to be described below, measurement of the $K^-\pi^-$ elastic cross section is equivalent to measuring the amount of the one-pion-exchange (OPE) process diagramed in Fig. 1(a). Because of the large π^+p elastic cross section in the region of the Δ^{++}, one expects that OPE, if it occurs, is most likely to be present if the π^+p system forms a Δ^{++}. We therefore select for analysis only those events having a π^+p invariant mass M, such that $1.14 < M < 1.31$ GeV. To further increase the probability of detecting whatever OPE contribution may be present, we limit the four-momentum transfer squared from the target proton to the Δ^{++} to $|t| < 0.3$ GeV^2 (t is negative in the physical region). As the invariant mass m of the $K^-\pi^-$ system increases, $|t|_{\min}$ also increases, thereby increasing the extrapolation distance to the pion pole and making the extrapolated values less reliable. Therefore we have performed extrapolations only for $m < 0.84$ GeV. Table I gives the amounts of the various resonances present in the 836 events which meet these three criteria.

Figure 2 shows histograms of m, M, and $|t|$. Also shown in Fig. 2 are the π^-p and $K^-\pi^+$ invariant masses and the four-momentum transfer squared from the target proton to the π^-p system for the 836 events in the selected sample. The superimposed curves are the predictions by a model to be discussed below. It is evident from Fig. 2(d) as well as Table I that most of the background to reaction (1) in our selected sample comes from reaction (2).

Our Chew-Low extrapolation technique consists

TABLE I. Amounts of resonance production before and after the following cuts: $m< 0.84$ GeV, $|t_{\pi^+p}| < 0.3$ GeV^2, $1.14 < M < 1.31$ GeV. Here, m is the $K^-\pi^-$ mass; M, the π^+p mass; and t_{π^+p}, the four-momentum transfer squared from the target proton to the π^+p system.

	2.05 GeV/c		2.05 GeV/c	
	Before cuts	After cuts	Before cuts	After cuts
Nonresonant	14%	~0	30%	~0
$Y^{*0}(1520)$	13%	4%	7%	~0
$\Delta^{++}(1236)$	46%	71%	27%	57%
$K^{*0}(890)\Delta^0(1236)$	18%	14%	5%	14%
Other $K^{*0}(890)$	9%	11%	31%	29%

of extrapolating the function

$$\sigma(t, m, M) = \frac{d^3\sigma}{dt\,dm\,dM} \bigg/ \left(\frac{d^3\sigma}{dt\,dm\,dM}\right)_{\mathrm{OPE}} \qquad (3)$$

to the unphysical point $t = m_\pi^2$. The numerator is the experimentally measured differential cross section for reaction (1), and the denominator is the calculated differential cross section for the OPE process shown in Fig. 1(a). Explicitly,

$$\left(\frac{d^3\sigma}{dt\,dm\,dM}\right)_{\mathrm{OPE}} = \frac{(1/\hbar c)^2}{4\pi^3 p_L^2 M_p^2}\,\frac{1}{(t-m_\pi^2)^2} \times m^2 q\sigma(m) M^2 Q\sigma(M) F(t, m, M)\,. \qquad (4)$$

In Eq. (4) the quantities t, m, and M are as defined above; M_p is the proton mass; m_π, the pion mass; q, the K^- momentum in the $K^-\pi^-$ rest frame; Q, the momentum of the π^+ in the π^+p rest frame; $\sigma(M)$, the real π^+p elastic cross section; and p_L, the laboratory beam momentum; further, $\sigma(m)$

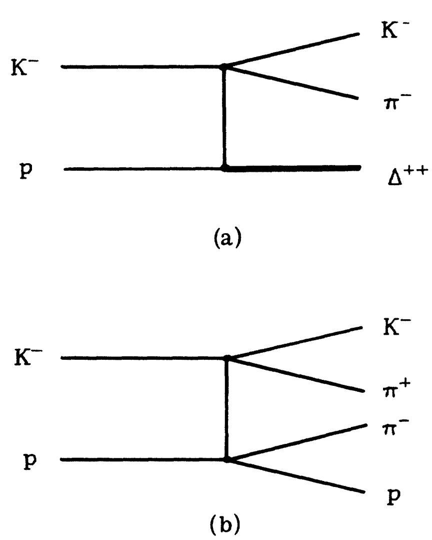

FIG. 1. (a) The OPE process used to determine the $K^-\pi^-$ elastic cross section. (b) The OPE process which contributes most of the background in our data.

is the real $K^-\pi^-$ elastic scattering cross section, which is set to 1 mb for calculating (3). The function $F(t, m, M)$ is a form factor to aid the extrapolation: It has the property that $F(m_\pi^2, m, M) = 1$. If the assumptions discussed below are true, then $\sigma(m_\pi^2, m, M)$ is the real $K^-\pi^-$ elastic cross section $\sigma_{3/2}(m)$. Note that since $(d^3\sigma/dt\,dm\,dM)_{\mathrm{OPE}}$ is linearly related to $\sigma(m)$, measuring $\sigma(m)$ is equivalent to measuring the amount of the OPE process shown in Fig. 1(a).

In this experiment statistics are limited and, as can be seen from Fig. 2(d), background is a serious problem. In order to minimize the uncertainty in the result due to the extrapolation procedures, we have employed a form factor $F(t, m, M)$ derived by Dürr and Pilkuhn,[7-9] which has been found in other experiments to approximately describe pion-exchange differential cross sections.[8,10-12] In particular, by extrapolating to the pion pole in the reaction $pp \to p\pi^+n$ at 6.6 GeV/c, Ma *et al.*[13] have shown that by using the Dürr-Pilkuhn prescription one can obtain values for the elastic π^+p cross section which agree completely with the known values, whereas a simple OPE model with $F(t, m, M) \equiv 1$ gives incorrect results. This work indicates that one can obtain meaningful results from a pole extrapolation, and also that the Dürr-Pilkuhn form factor adequately describes the $\Delta^{++}(1238)$ vertex. We have, in addition, made background subtractions which are described below.

If $F(t, m, M)$ correctly accounts for off-mass-shell effects, i.e., if Eq. (4) correctly describes the OPE process throughout the physical region, and if there were no background in our sample, then measurements of $\sigma(t, m, M)$ would yield values independent of t and M and equal to $\sigma_{3/2}(m)$. In general, however, neither is true. In particular, one does not expect the Dürr-Pilkuhn form factor to be correct if the outgoing particles at the $K\pi$ vertex are in an S wave.[14] Therefore, $\sigma(t, m, M)$ can be equal to $\sigma_{3/2}(m)$ only at the exchange pole $t = m_\pi^2$. If, however, $\sigma(t, m, M)$ is a continuous function of t with continuous derivatives – especially if it monotonically approaches $\sigma_{3/2}(m)$ as t

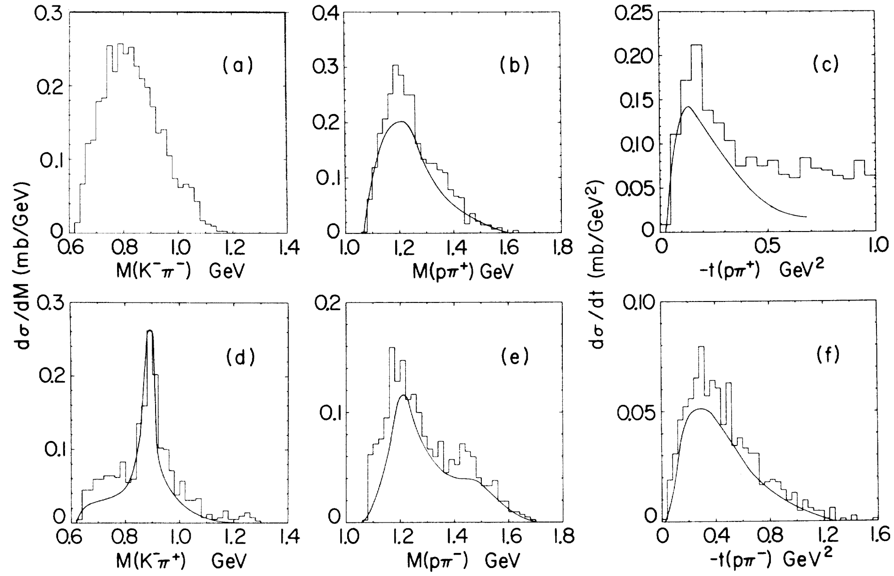

FIG. 2. (a) $(d\sigma/dM)_{K^-\pi^-}$ for those events satisfying $1.14 < M_{\pi^+p} < 1.31$ GeV and $|t| < 0.3$ GeV^2. (b) $(d\sigma/dM)_{\pi^+p}$ for those events satisfying $M_{K^-\pi^-} < 0.84$ GeV and $|t| < 0.3$ GeV^2. (c) $d\sigma/dt$ for those events satisfying $M_{K^-\pi^-} < 0.84$ GeV and $1.14 < M_{\pi^+p} < 1.31$ GeV. (d), (e), (f) $(d\sigma/dM)_{K^-\pi^+}$, $(d\sigma/dM)_{\pi^-p}$, $(d\sigma/dt)_{\pi^-p}$ for those events satisfying $M_{K^-\pi^-} < 0.84$ GeV, $1.14 < M_{\pi^+p} < 1.31$ GeV, and $|t| < 0.3$ GeV^2.

approaches m_π^2 – and if the background is less forward peaked than $(t - m_\pi^2)^{-2}$ near the boundary of the physical region, then it is possible to estimate $\sigma_{3/2}(m)$ by extrapolating measurements of $\sigma(t, m, M)$ from the physical region to $t = m_\pi^2$.

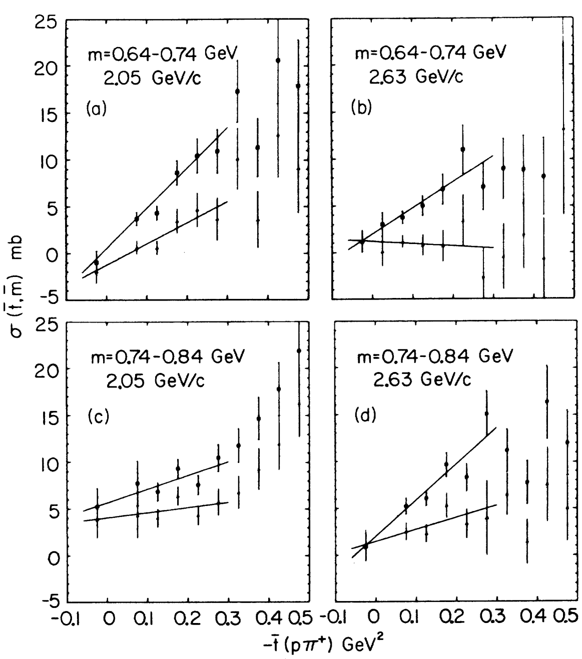

FIG. 3. Plots of $\sigma(\bar{t}, \bar{m})$ vs $\bar{t}$. Square data points are for no background subtraction, and triangular data points are with background subtracted as described in the text.

The less accurate the measurements of $\sigma(t, m, M)$, and the larger the background in the sample, the more important it is that $\sigma(t, m, M)$ be a well-behaved slowly varying function of t.

The extrapolation is performed in two 0.1-GeV intervals in $K^-\pi^-$ invariant mass m, starting at 0.64 GeV. Each of these intervals is subdivided into intervals in $|t|$. For each of these subintervals the quantity

$$\sigma(\bar{t}, \bar{m}) = \frac{\int_{\Delta m,\, \Delta M,\, \Delta t} \frac{d^3\sigma}{dt\,dm\,dM}\, dt\,dm\,dM}{\int_{\Delta m,\, \Delta M,\, \Delta t} \left(\frac{d^3\sigma}{dt\,dm\,dM}\right)_{\text{OPE}} dt\,dm\,dM} \tag{5}$$

is evaluated, where the integral is over the regions defined by the intervals in t, m, and M, and $\bar{t}$ and $\bar{m}$ are the mean values of $|t|$ and m in each of these intervals.

Figure 3 plots $\sigma(\bar{t}, \bar{m})$ as a function of $\bar{t}$ for each of the four intervals in m (square data points). As can be seen, these measurements show a strong dependence on $\bar{t}$. This is not surprising, because of the large amount of background known to be in the sample.

As observed above, the OPE reaction (2), depicted in Fig. 1(b), is a major contributor to the background. This reaction and other reactions which produce $K^{*0}(890)\pi p$ have been shown to be well described by using an OPE model with Dürr-Pilkuhn form factors, especially when the πp system forms a $\Delta(1238)$.[10,15] The description and use

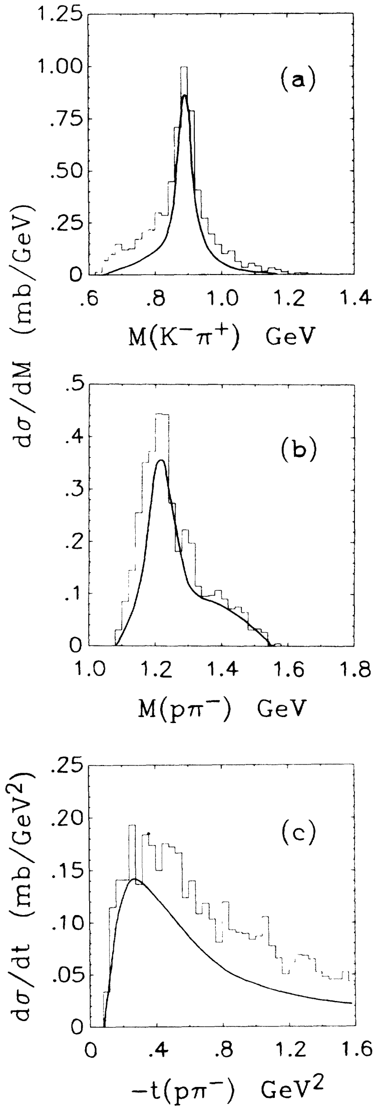

FIG. 4. (a) $(d\sigma/dM)_{K^-\pi^+}$ for those events having $|t_{\pi^-p}| < 0.5$ GeV^2. (b) $(d\sigma/dM)_{\pi^-p}$ for those events satisfying $|t_{\pi^-p}| < 0.5$ GeV^2 and $0.84 < M_{K^-\pi^+} < 0.98$ GeV. (c) $(d\sigma/dt)_{\pi^-p}$ for those events satisfying $0.84 < M_{K^-\pi^+} < 0.98$ GeV.

of $F(t, m, M)$ for the background process involving low-energy π^-p scattering are given elsewhere.[16] Since the $K^-\pi^+$ elastic scattering cross section has been measured in other experiments,[10] we may use this information to calculate the contribution of reaction (2) to the background, assuming incoherence of the production amplitudes. This contribution can be subtracted from the experimentally measured $d^3\sigma/dtdmdM$ to reduce the effect of the background on the extrapolation. Figure 4 plots $(d\sigma/dm)_{K^-\pi^+}$, $(d\sigma/dm)_{\pi^-p}$, and $(d\sigma/dt)_{\pi^-p}$ to illustrate the extent to which the above OPE model describes the background [Reaction (2)]. The curves are the model predictions.

Figure 3 also plots $\sigma(\bar{t}, \bar{m})$ as measured for this background-subtracted sample (triangular data points). As can be seen, this background subtraction has dramatically reduced the dependence of $\sigma(\bar{t}, \bar{m})$ on $\bar{t}$.

Linear fits of the form $a - bt$ were attempted for both sets of $\sigma(\bar{t}, \bar{m})$, and in each case the points at $-t = -0.02$ GeV^2 represent the extrapolated value and the associated statistical error. Only the points with $|t| < 0.3$ GeV^2 were used in the fits. Table II summarizes the results of these fits, including fit parameters, extrapolated cross sections, and the associated statistical errors. The $\sigma_{3/2}(m)$ is obtained by averaging the background-subtracted results for the 2.05- and 2.63-GeV/c samples for each bin in m.

In order to check that the background subtraction is reasonable, we have calculated the differential cross sections $d\sigma/dM$, $d\sigma/dt$, $(d\sigma/dt)_{\pi^-p}$, $(d\sigma/dM)_{\pi^-p}$, and $(d\sigma/dm)_{K\pi^+}$ for our selected sample of data, assuming that only reactions (1) and (2) contribute incoherently to the sample. The contribution from reaction (1) is calculated by inserting our extrapolated value of $\sigma_{3/2}(m)$ in Eq. (4). We assume for this purpose that $\sigma_{3/2}(m)$ is 0 in the range 0.64–0.74 GeV, since the extrapolated cross section is slightly negative in this region. These extrapolated differential cross sections are plotted as the solid lines superimposed upon the corresponding experimentally measured quantities in Figs. 2(b)–2(f). Apart from the normalization being somewhat low, this simple calculation gives a reasonably good description of these data. This is a reflection of the small slopes of $\sigma(t, m)$ as a function of $\bar{t}$ for the subtracted extrapolations. The discrepancies between the calculation and the data could be due to the inadequacy of the calculation, the presence of some remaining background, or a combination of both. We emphasize that we deduce nothing directly about the $K^-\pi^-$ elastic cross section from the extent to which the curves of Fig. 2 describe the data. These figures illustrate only that reaction (2) is a large contributor to the background and that our procedure for calculating and subtracting this contribution is reasonable. In fact, the extrapolated cross sections obtained with background subtracted are essentially the same as those obtained before background subtraction.

In Fig. 5 the results of our background-subtracted extrapolations are presented along with the results of other attempts to measure the $T=\frac{3}{2}$ $K\pi$ elastic scattering cross section. In interpreting our results it is important to keep in mind the uncertainty inherent in this extrapolation procedure. The errors indicated on our measurements

TABLE II. Results of fits of the experimental points shown in Fig. 3 to the assumed form $\sigma(t)=a-bt$.

Data set	Fit quantities	$K^-\pi^-$ mass range (GeV) 0.64–0.74 2.05 GeV/c	0.64–0.74 2.63 GeV/c	0.74–0.84 2.05 GeV/c	0.74–0.84 2.63 GeV/c
Background in	Confidence level (%)	35	66	26	17
	a (mb)	-0.1 ± 1.1	1.7 ± 1.0	5.5 ± 1.9	1.7 ± 1.4
	b (mb/GeV^2)	43.0 ± 8.7	27.8 ± 8.8	14.8 ± 9.8	38.6 ± 9.2
	$\sigma_{\rm extrap}$ (mb)	-1.0 ± 1.2	1.1 ± 1.1	5.2 ± 2.0	0.9 ± 1.4
Background out	Confidence level (%)	48	65	33	46
	a (mb)	-1.5 ± 1.1	1.2 ± 1.1	4.0 ± 1.9	1.3 ± 1.6
	b (mb/GeV^2)	22.6 ± 8.7	-2.5 ± 10.1	5.4 ± 9.9	12.9 ± 11.1
	$\sigma_{\rm extrap}$ (mb)	-1.9 ± 1.2	1.2 ± 1.2	3.9 ± 2.0	1.1 ± 1.7
	av $\sigma_{\rm extrap}$ (mb)	-0.3 ± 0.9		2.3 ± 1.3	

are just the statistical ones that are propagated from the least-squares fit to the linear form for $\sigma(\bar{m}, \bar{t})$. Although it might be reasonable to assume that $\sigma(t, m, M)$ is a well-behaved function of t, there is nothing that requires it. Also, it is reasonable to assume that the background is less peaked in the forward direction than $(t-m_\pi^2)^{-2}$, but again, *a priori*, there is nothing to require it. To the extent that these assumptions are not true there will be systematic errors in interpreting the extrapolated results as the $K^-\pi^-$ elastic cross section.[17]

Cho *et al.*[18] obtain the $K^-\pi^-$ elastic cross section by performing a pole extrapolation, using the reaction $K^-n\to K^-\pi^-p$. For this reaction the equation for $\sigma(t, m)$ analogous to Eq. (4) has a pole at $t=0$ unless $d^2\sigma/dtdm$ has a zero there. Any contribution to $d^2\sigma/dtdm$ other than simple one-meson exchange in general gives a nonzero contribution to the amplitude at $t=0$. Cho *et al.* assume no such contribution and therefore constrain $\sigma(t, m)$ to be finite at $t=0$.

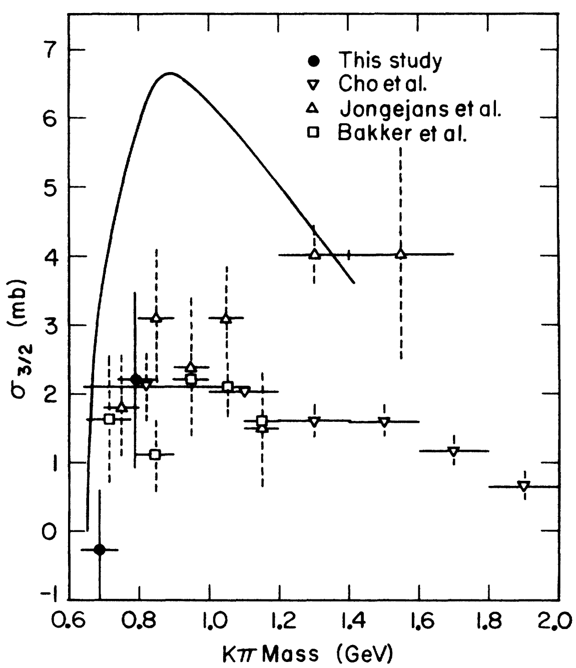

FIG. 5. Summary of measurements of the $T=\frac{3}{2}$ $K\pi$ elastic cross section. Curve is the prediction of a Veneziano model of Lovelace.

Jongejans *et al.*[19] perform a pole extrapolation, using 669 events of the type $K^-p\to K^-\pi^-\Delta^{++}$, where the momentum transfer squared to the Δ^{++} is less than 0.4 GeV^2. They use a maximum-likelihood polynominal fit to describe the t dependence of their extrapolation function. They do not account for the $K^{*0}(890)\pi^-p$ background in their sample. They point out that the values they quote for the highest two bins in $K\pi$ mass may be unreliable, since the smallest accessible value of $|t|$ for these bins is rather large, 0.2 GeV^2.

Bakker *et al.*[20] perform a pole extrapolation, using 1009 events of the type $K^-n\to K^-\pi^-p$ having a momentum transfer squared to the nucleon less than 0.32 GeV^2. They find that their results are not substantially different whether or not they use a form factor to describe the t dependence of their extrapolating function, which is well fitted by a straight line.

Antich *et al.*[21] have used the reaction $K^-n\to K^-\pi^-p$ at 12 GeV/c to determine $\sigma_{3/2}$. With limited statistics, they find that $\sigma_{3/2}=5\pm0.4$ mb over the range $M(K^-\pi^-)<1.5$ GeV. They use a pole extrapolation with no form factors.

In addition, phase-shift analyses[22,23] have been performed by using the high-statistics data of the International K^+ Collaboration on the reaction $K^+p\to K^0\pi^0\pi^+p$ $(K^+\pi^-\pi^+p)$ in which both $K^+\pi^-$ elastic and charge-exchange scattering were studied. In each case there is a solution for $\delta_{3/2}$ which is compatible with our results on $\sigma_{3/2}$ and the summary in Fig. 5.

Yuta *et al.*[24] have analyzed the final states

$K^-p\to K^-\pi^+n$ and $K^-p\to \bar{K}^0\pi^-p$ at 5.5 GeV/c. They perform a partial-wave analysis in which the angular moments are parametrized by using a nonabsorptive one-particle-exchange model involving both scalar and vector exchanges. Taking the absolute value of $\delta_{3/2}$ from measurements of $\sigma_{3/2}$, Yuta *et al.* find the sign of $\delta_{3/2}$ to be negative.

The solid curve on Fig. 5 is the $T=\frac{3}{2}$ cross section as predicted by the Veneziano model of Lovelace.[3] Although $\delta_{3/2}$ is predicted to be negative, as found by Yuta *et al.*, the calculated cross section overestimates our measurements as well as the others shown in the figure.

Current algebra predicts[4] S-wave $K\pi$ scattering lengths of $a_{1/2}=0.26$ F, $a_{3/2}=-0.13$ F, corresponding to a threshold cross section for the reaction $K^-\pi^-\to K^-\pi^-$ of 2.1 mb. This number is consistent with the results of Fig. 4.[25]

Clearly reaction (1) is not an ideal approach to the study of the $T=\frac{3}{2}$ $K\pi$ cross section, especially at low momentum. However, neither can any experiment thus far done be considered ideal. Most recent experiments involve the use of three-body final states, which have the advantages of minimal background and low values of $|t|_{\min}$. As mentioned earlier one must assume the absence of a singularity in the extrapolating function at $t=0$, or at least that its presence can be ignored. It has been shown[26] that considerable systematic errors can thereby arise.

On the other hand, a four-body final-state analysis is complicated by the presence of considerable background. Whether meaningful results can be obtained depends to a large degree on the nature and amount of this background. For example, one could not put much faith in an extrapolation using the reaction $K^+p\to(K^+\pi^+)(\pi^-p)$, since the background $[K^{*0}(890)\Delta^{++}(1236)]$ is exceedingly strong.[27] We have attempted to show that for reaction (1), in which the background is considerable but not overwhelming, one can explicitly calculate the effect of the background on the determination of $\sigma_{3/2}$. Our confidence in our results is strengthened by the fact that $\sigma_{3/2}$ is essentially the same both before and after background subtraction.

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Search for Magnetic Monopoles in Lunar Material*

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A search for magnetic monopoles in lunar material has been performed by the electromagnetic measurement of the magnetic charge of samples. All measurements were found consistent with zero charge for all samples and inconsistent with any other value allowed by the Dirac theory. Upper limits are determined for the monopole flux in cosmic radiation and for the pair-production cross section in proton-nucleon collisions.

I. INTRODUCTION

An electromagnetic monopole detector has been used to measure the magnetic charge of samples of lunar material returned by the Apollo 11 mission. The null result and a preliminary interpretation have been reported.[1] This paper gives a more complete analysis of the experiment.

The discovery of magnetic monopoles would have far-reaching consequences. Their existence has been invoked in the explanation of the phenomenon of electric charge quantization,[2,3] a phenomenon which has been verified to the limit of experimental accuracy.[4] According to a recent theory,[5] the elementary particles would be made of electrically charged monopoles, i.e., particles having both an electric and a magnetic charge.

All searches for monopoles rely on some physical properties attributed to those particles. The failure to discover them in a given experiment calls for careful documentation of the monopole properties that were assumed and for an assessment of their likelihood. A "legalistic" point of view may be appropriate to judge the proofs of absence of monopoles in such an experiment. All the properties assumed in our detection technique stem from long-range interactions, i.e., the only interactions for which reliable predictions can be computed when the coupling constant is as large as the one expected for magnetic monopoles.

In Sec. II we describe the basic properties of the monopole, and in Sec. III we discuss some experimental consequences based on them. In Sec. IV we describe our measurements of the magnetic charge of 28 samples of lunar material. Interpretation of our negative result in terms of limits for the cosmic-ray flux and the production cross sections depends on the history of the lunar surface, for which reasonable hypotheses are advanced; that history justifies the search for monopoles in the lunar material. These hypotheses cannot be paralleled to the properties assumed for the detection technique. They are described and used to interpret our data in Secs. V, VI, and VII. Some measurements performed on different material with the same equipment and the limit we have obtained for the monopole density in ordinary matter are reported in Sec. VIII. Some remarks about the present experimental situation are given in Secs. IX and X.

II. BASIC PROPERTIES OF MONOPOLES

In classical electrodynamics, a magnetic monopole is a particle that possesses a magnetic charge