# MEASUREMENT OF THE REAL PART OF THE FORWARD SCATTERING AMPLITUDE IN K ${ }^{ \pm} \mathrm{p}$ ELASTIC SCATTERING AT 10.4 AND $14 \mathrm{GeV} / \mathrm{c}$＊ 

R．K．Carnegie，R．J．Cashmoret，M．Davier，<br>D．W．G．S．Leith，F．Richard $\dagger \dagger$ ，P．Schacht ${ }^{⿻}$ ， P．Walden毒，and S．H．Williams<br>Stanford Linear Accelerator Center Stanford University，Stanford，California 94305


#### Abstract

The differential cross section for $\mathrm{K}^{ \pm} \mathrm{p}$ elastic scattering has been measured in the very low $t$ region（． $003<\mathrm{t}<.2 \mathrm{GeV}^{2}$ ）in a wire cham－ ber spectrometer experiment at 10.4 and $14 \mathrm{GeV} / \mathrm{c}$ ．The interference effect observed between the Coulomb and the nuclear interaction has been used to determine $\alpha$ ，the ratio of real to imaginary part of the forward scattering amplitude．At $10.4 \mathrm{GeV} / \mathrm{c}$ we measure $\alpha\left(\mathrm{K}^{+} \mathrm{p}\right)=$ $-.21 \pm .06$ and $\alpha\left(\mathrm{K}^{-} \mathrm{p}\right)=.08 \pm .04$ ，and at $14 \mathrm{GeV} / \mathrm{c}, \alpha\left(\mathrm{K}^{+} \mathrm{p}\right)=-.13 \pm .03$ and $\alpha\left(\mathrm{K}^{-} \mathrm{p}\right)=.00 \pm .04$ in agreement with the predictions of dispersion theory calculations．


（Submitted for publication）

[^0]The differential cross sections for $K^{ \pm} p$ elastic scattering at 10.4 and 14 $\mathrm{GeV} / \mathrm{c}$ have been measured in a wire chamber spectrometer [1] at SLAC. The interference effect between Coulomb and nuclear scattering observed in the small angular region has been used to determine the real part of the $K^{ \pm} p$ forward scattering amplitude. Two different geometries were used to provide measurement of the elastic angular distribution within $3<\theta<50 \mathrm{mrad}$, and $7<\theta<100$ mrad respectively. The latter data set provided a high statistics measurement of the nuclear scattering [2] with identical experimental conditions for $\mathrm{K}^{+} \mathrm{p}$ and $\mathrm{K}^{-} \mathrm{p}$ while the former was taken to supplement the data in the small angle region for the $\mathrm{K}^{+} \mathrm{p}$ data. The results of the analysis of both $\mathrm{K}^{+} \mathrm{p}$ geometries agree with each other. $\mathrm{K}^{+} \mathrm{p}$ and $\mathrm{K}^{-} \mathrm{p}$ measured real parts satisfy the predictions of dispersion relations calculations [3].

The experiment has been performed at SLAC in a radiofrequency separated beam of high purity-typically $90 \%$-and used the two different geometries shown schematically in fig. 1. Beam tracks were measured by two scintillation counter hodoscopes and four proportional planes with 1 mm spacing. The scattered tracks were measured by nine magnetostrictive chambers, each with four read out planes, mounted in two packages on each side of the large aperture magnet. In the elastic geometry, the magnetostrictive chambers and the trigger hodoscopes were desensitized in the beam region in order to accept a high instantaneous beam flux ( 3 MHz ) whereas in the Coulomb geometry the beam flux is reduced by about an order of magnitude and the small angle acceptance is unbiased by offsetting the desensitized region of the spark chambers and hodoscopes (see fig. 1).

We triggered on only one particle through the spectrometer coming from an interacting kaon, identified by two Cerenkov counters in the beam. A four sector
counter, XY, surrounded by a veto ring counter was used to monitor the beam and as a veto for multiple beam events within the trigger logic time gate. The target was 1 m long and 5 cm diameter, and immediately downstream there was a three-plane proportional chamber with 1 mm spacing, which had an active area of $\pm 2.5 \mathrm{~cm}$. Decay muons were vetoed using a large aperture Cerenkov counter, C, with $2.5 \mathrm{~m} \times 1 \mathrm{~m}$ aperture. In addition, muons were tagged using a detection system consisting of three $60 \mathrm{~cm} \times 60 \mathrm{~cm}$ scintillation counters each separated by 60 cm of iron. In the Coulomb geometry the beam was focused on a small ( 5 cm diameter) veto counter which was 8 m downstream of the hydrogen target.

The incident particle momentum is known to $\pm .25 \%$, while the scattering angle resolution was continuously monitored by triggering on beam particles and measuring tracks in the spectrometer. The scattering angle resolution deduced from these studies was 1.0 mrad . The missing mass square resolution had a standard deviation of $.250 \mathrm{GeV}^{2}$ at $14 \mathrm{GeV} / \mathrm{c}$.

The elastic scattering events were identified using the following cuts: $-\chi^{2} \leq 25$ for the scattered track, which is defined with 15 degrees of freedom maximum.

This selection rejects poorly measured events, thus improving the scattering angle resolution.

- Missing mass squared cut of $\pm 1.2 \mathrm{GeV}^{2}$ around the central value This selection identifies a clean sample of elastic events with 2-3 percent inelastic background.
- Cut on the longitudinal position of the vertex, defined as the point of minimum distance between the incident beam track and the scattered track.

This last cut was tighter at small angles to minimize the nonhydrogen contributions (target walls, XY counter, proportional chambers) so that the empty target subtraction remained small. In doing so, we introduced an angular dependent effect, which was corrected for by fitting the longitudinal vertex (Z), distribution for every 1 mrad angular bin and computing the loss of good events. Table 1 summarizes the full and empty target data obtained in this experiment.

In the small angle region we had to apply several other corrections. For the Coulomb geometry the veto counter begins to veto events at angles below 5 mrad. This effect is properly taken care of by a Monte Carlo program using the continuously measured beam tracks as input. For angles smaller than 5 mrad , the corrections for the angular resolution also become important since the Coulomb cross section varies so rapidly in this region. In doing the empty target subtraction, we took into account the difference in resolution between full and empty target measurements.

For the elastic geometry the chambers were blinded in the beam region over $\pm 1.5 \mathrm{~cm}$ so that the acceptance corrections are important at small scatter ing angles. These corrections were also made by folding in the directly measured beam tracks within the Monte Carlo program.

We used the following expression for the parametrization of the scattering angular distribution

$$
\frac{d N}{d t}=F\left[A_{N}^{2}\left(1+\alpha^{2}\right) M_{N}+A_{C}^{2} M_{C}-2 Q A_{N} A_{C}(\alpha \cos \delta+Q \sin \delta) M_{I}\right]
$$

where

$$
\begin{aligned}
& A_{C}=.0161 t^{-1}(1+t / .71)^{-4} \\
& A_{N}=.227 \sigma_{T} e^{-b t / 2-c t^{2} / 2}
\end{aligned}
$$

F normalization factor
$\alpha$ ratio of real to imaginary nuclear amplitude
b nuclear slope
c curvature
Q charge of the incident particle
$t$ momentum transfer in $\mathrm{GeV}^{2}$
$\sigma_{\mathrm{T}}$ total cross section in mb
$\delta=-[\ln [(\mathrm{b} / 2+5.6) \mathrm{t}]+.577] / 137$ Coulomb phase shift taken from ref. [4].
$\mathrm{M}_{\mathrm{N}}, \mathrm{M}_{\mathrm{C}}, \mathrm{M}_{\mathrm{I}}$ are the multiple scattering terms and can be derived using Moliere's theory $[5,6]$. In the fitting domain one can derive approximate expressions:

$$
\begin{aligned}
& M_{\mathrm{C}}=\left[1-5\left(\theta_{\mathrm{S}} / \theta\right)^{2}\right]-4 / 5 \\
& \mathrm{M}_{\mathrm{I}}=1+2\left(\theta_{\mathrm{S}} / \theta\right)^{2} \\
& \mathrm{M}_{\mathrm{N}}=1-2.1610^{-4}\left(\sigma_{\mathrm{T}}^{2} / \mathrm{b}\right)\left[1-.25 \mathrm{e}^{\mathrm{bt} / 2}\right]
\end{aligned}
$$

where $\theta_{S}$ is the multiple scattering angle defined in ref. [5]. To account for the experimental resolution itself, we have folded a Gaussian distribution, using the experimentally determined width, over the theoretical expression weighted by our acceptance. At 3 mrad and 14 GeV , this effect increases $\mathrm{dN} / \mathrm{dt}$ by $17 \%$, but is already negligible at 6 mrad . In doing our calculation, we admitted implicity that there was no strong corrclation between angular spread and vertex position spread. If there werc a corrclation the effect should be small since some of these extra events would lie outside the cut on the $Z$ distribution. The data favor the no-correlation hypothesis and further we see no significant dependence of our result with the $Z$ cut.

The folded theoretical values are then compared to the measurements and a fit is performed allowing $b, \alpha$ and the normalization $F$ to vary. $\sigma_{\mathrm{T}}$ is taken from ref. [7] and its error is incorporated in the determination of $\alpha$. Due to limited statistics for the $10.4 \mathrm{GeV} / \mathrm{c} \mathrm{K}^{+} \mathrm{p}$ Coulomb data, we have constrained the nuclear slope to the value found from the elastic events. Table 2 summarizes our results and fig. 2 shows the $\mathrm{d} \sigma / \mathrm{dt}$ distributions for 10.4 and $14 \mathrm{GeV} / \mathrm{c}$ for $\mathrm{K}^{+} \mathrm{p}$ and $\mathrm{K}^{-} \mathrm{p}$ scattering together with the fitted curves. For $\mathrm{K}^{+} \mathrm{p}$ scattering the results from the separate Coulomb and elastic geometry data samples are in good agreement. Notice that for the Coulomb $\mathrm{K}^{+} \mathrm{p}$ data, the fits extend to smaller $t$ values than needed to measure the interference effect. By doing this we do not gain much in accuracy but we are able to check that the corrections are well understood. By varying the low momentum transfer cut off for each fit, we can study the small changes in the results and thus get an estimate of the systematic errors quoted in table 2.

In the fit, a small $t$ dependence of the slope was included. We used the curvature c obtained from the high statistics elastic data [8]. Also the real part could have a different t slope than the imaginary; however this has no practical effect on the measurement of the real part because of the very restricted $t$ region of interference: if the real part slope were half that of the imaginary part it would result in only a $1 \%$ variation of $\alpha$.

In fig. 3 we compare our results with the predictions of $t=0$ dispersion relations [3] including recent data on total cross sections [9]. There is agreement for both the 10.4 and 14 GeV results whereas the previous indirect determinations [10] are ruled out.

Within the framework of duality, the $K^{+} p$ scattering is exotic in the s-channel and should have strong cancellation for the imaginary parts of the nondiffractive
t-channel exchange amplitudes, but not for the real parts. This should lead to a large ratio, $\alpha$, of the real to imaginary parts at low energies. As the energy increases the nondiffractive amplitudes will grow smaller, and one expects the ratio, $\alpha$, to also grow smaller. In addition, for a scattering process in which the total cross section increases at high energy*, the ratio $\alpha$ is required by analyticity and crossing [11] to pass through zero and become positive. An indication of this phenomenon is seen in our $\mathrm{K}^{+}$data at 10.4 and $14 \mathrm{GeV} / \mathrm{c}$, and is an independent confirmation of the precocious high energy behavior of the $\mathrm{K}^{+} \mathrm{p}$ system. In contrast, the $\mathrm{K}^{-} \mathrm{p}$ system is not exotic in the s -channel leading to a larger imaginary part, while the real part is strongly reduced at $t=0$. Our measured values for $\alpha$ are indeed very small and support the duality picture.

We would like to thank G. Brandenburg and J. Matthews for their contributions during the data taking stage of this experiment.

[^1]
## References

[1] G. W. Brandenburg et al., to be submitted to Nucl. Inst. and Meth.
[2] G. W. Brandenburg et al., to be published, SLAC-PUB-1607 (1975).
[3] R. E. Hendrick and B. Lautrup, Rockfeller University report COO-2232B-62.
[4] G. W. West and D. R. Yennie, Phys. Rev. 172, 1413 (1968);
M. F. Locher, Nucl. Phys. 132, 525 (1967).
[5] H. A. Bethe, Phys. Rev. 89, 1256 (1953).
[6] R. K. Carnegie et al., to be published.
[7] W. Galbraith et al., Phys. Rev. 138, B913 (1965);
S. Denisov et al., Phys. Letters 36B, 415 (1971).
[8] R. K. Carnegie et al., to be published, SLAC-PUB-1609 (1975).
[9] A. S. Carroll et al., Phys. Rev. Letters 33, 932 (1974).
[10] K. J. Foley et al., Phys. Rev. Letters 11, 503 (1963).
[11] N. Khuri and T. Kinoshita, Phys. Rev. B 140, 706 (1965).
See also J. Bronzan et al., Phys. Letters 49B, 272 (1974).
[12] P. Baillon et al., Phys. Letters 50B, 377 (1974).
[13] T.H.J. Bellm et al., Nuovo Cimento Letters 3, 389 (1970).
[14] T.H.J. Bellm et al., Phys. Letters 33B, 438 (1970).
[15] J. R. Campbell et al., Nucl. Phys. B64, 1 (1973).
[16] Amsterdam-Nijmegen-Paris collaboration. See Meijer et al., Zeeman Laboratory, RX-672-Amsterdam (1974).

TABLE 1
Total data taken and number of events to extract the real part after reconstruction and cuts.

| Momentum (GeV/c) | Total Beam Flux ( $10{ }^{6}$ ) |  | Events Used in the Fit |
| :---: | :---: | :---: | :---: |
| $\mathrm{K}^{+} \mathrm{p}$ |  |  |  |
| $14 \mathrm{GeV} / \mathrm{c}$ |  |  |  |
| Coulomb | Full | 8.7 | 30,000 |
|  | Empty | 1.9 | 180 |
| Elastic | Full | 106.0 | 434,200 |
|  | Empty | 14.1 | 2,100 |
| $10.4 \mathrm{GeV} / \mathrm{c}$ |  |  |  |
|  | Full | 2.3 | 8,000 |
| Coulomb | Empty | . 2 | 70 |
| Elastic | Full | 28.2 | 123, 000 |
|  | Empty | 4.0 | 1,000 |
| $\mathrm{K}^{-} \mathrm{p}$ |  |  |  |
| $14 \mathrm{GeV} / \mathrm{c}$ |  |  |  |
| Elastic | Full | 42.9 | 211, 300 |
|  | Empty | 7.8 | 1,960 |
| $10.4 \mathrm{GeV} / \mathrm{c}$ |  |  |  |
|  | Full | 23.9 | 131, 700 |
| Elastic | Empty | 3.2 | 900 |

TABLE 2
Results of the fits. The errors in ( ) are the possible systematic errors associated with each measurement. The number of degrees of freedom DF is indicated besides the $\chi^{2}$. The limits of the fitted region are $t_{\min }$ and $t_{\max }$.

| Momentum $(\mathrm{GeV} / \mathrm{c})$ | Ratio of Real to Imaginary Amplitude $\alpha$ | Slope <br> b $\left(\mathrm{GeV}^{-2}\right)$ | $\begin{gathered} c \\ \left(\mathrm{GeV}^{-4}\right) \end{gathered}$ | $\chi^{2}(\mathrm{DF})$ | $\mathrm{t}_{\min }$ | $t_{\text {max }}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathrm{K}^{+} \mathrm{p}$ |  |  |  |  |  |  |
| 13.90 Coulomb | $-.10 \pm .05( \pm .01)$ | $6.15 \pm .15$ | -. 5 | 36 (54) | . 003 | 210 |
| 14.00 Elastic | $-.15 \pm .03( \pm .02)$ | $6.09 \pm .07$ | -. 5 | 49(34) | . 010 | . 180 |
| 10.40 Coulomb | $-.21 \pm .12$ | 5.68 | 0 | 35 (38) | . 001 | . 200 |
| 10.40 Elastic | $-.21 \pm .06( \pm .02)$ | $5.68 \pm .10$ | 0 | $38(30)$ | . 005 | 200 |
| $\mathrm{K}^{-} \mathrm{p}$ |  |  |  |  |  |  |
| 14.00 Elastic | . $00 \pm .04( \pm .03)$ | $8.14 \pm .07$ | -1.3 | 43(23) | . 010 | 200 |
| 10.40 Elastic | . $08 \pm .04( \pm .02)$ | $8.20 \pm .09$ | -1.6 | 41(33) | . 005 | 200 |

## Figure Captions

1. The two different setups used in this experiment are

$$
\begin{aligned}
& \text { Elastic trigger }=\overline{\mathrm{C}}_{\pi} \mathrm{C}_{\mathrm{K}}(\mathrm{XY}) \mathrm{HA} \cdot \mathrm{HB}(\overline{\mathrm{HA} \geq 2 \cdot \mathrm{HB}} \geq 2) \overline{\mathrm{M}} \cdot \overline{\mathrm{C}} \cdot \mathrm{~T} \\
& \text { Coulomb trigger }=\overline{\mathrm{C}}_{\pi} \mathrm{C}_{\mathrm{K}}(\mathrm{XY}) \mathrm{HA} \cdot \mathrm{HB}(\overline{\mathrm{HA} \geq 2 \cdot \mathrm{HB}} \geq 2) \overline{\mathrm{M}} \cdot \overline{\mathrm{C}} \cdot \overline{\mathrm{~V}}
\end{aligned}
$$

2. $K^{ \pm} p$ differential elastic scattering cross sections at $14 \mathrm{GeV} / \mathrm{c}$ (a) $\mathrm{K}^{-} \mathrm{p}$ elastic, (b) $\mathrm{K}^{+} \mathrm{p}$ elastic, (c) $\mathrm{K}^{+} \mathrm{p}$ Coulomb, (d) $\mathrm{K}^{+} \mathrm{p}$ Coulomb for $\mathrm{t}<.030$ $\mathrm{GeV}^{2}$ and at $10.4 \mathrm{GeV} / \mathrm{c}$, (e) $\mathrm{K}^{-} \mathrm{p}$ elastic, (f) $\mathrm{K}^{+} \mathrm{p}$ elastic, (g) $\mathrm{K}^{+} \mathrm{p}$ Coulomb, (h) $\mathrm{K}^{+} \mathrm{p}$ elastic for $\mathrm{t}<.030 \mathrm{GeV}^{2}$. The lines shown are the fits described in the text. The fit starts at a $t$ value indicated by an arrow. In $d$ and $h$ the separate contributions from pure Coulomb (---) and interference (-.-.) terms are given.
3. Comparison of $\operatorname{Rc}\left(\mathrm{K}^{ \pm} \mathrm{p}\right) / \operatorname{Im}\left(\mathrm{K}^{ \pm} \mathrm{p}\right)$ measurements with dispersion relations predictions [3] (hatched area). All experimental results displayed measure the interference effect.
(a) $\mathrm{K}^{+} \mathrm{p}$ measurements: - This experiment, $\Delta$ ref. [12], ©ref. [13].
(b) $\mathrm{K}^{-} \mathrm{p}$ measurements: •This experiment, $\Delta$ ref. [12], ref. [14], $\times$ ref. [15], ref. [16].


Fig. 1


Fig. 2


Fig. 3


[^0]:    ＊Work supported by the U．S．Energy Research and Development Administration． $\dagger$ Now at the Department of Physics，Oxford University，Keble Road，Oxford， England．
    $\dagger$ †On leave from Laboratoire de l＇Accélérateur Linéaire，Université Paris－Sud， 91－Orsay，France．
    
    轉Now at TRIUMF，University of British Columbia，Vancouver，B．C．，Canada．

[^1]:    *This is the case for the $K^{ \pm} p$ total cross sections as measured in ref. [9].

