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K^-p INTERACTION AROUND 1 GeV/c
PRELIMINARY RESULTS OF A PHASE SHIFT ANALYSIS *

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I wish to present a summary on the recent work of the CERN-Heidelberg-Saclay collaboration.[1] The data come from a systematic K^-p bubble chamber investigation using the Saclay 81 cm HBC in a low momentum separated K^- beam[2] at the CERN P. S. An exposure of about 150,000 pictures (with hydrogen), were taken at 23 different momenta in the range of ~ 800 - 1200 MeV/c. The momentum values are shown in Table I. The average momentum spread at the entrance to the chamber is of order $\pm$ 10 MeV/c. The yield of the experiment is ~ 0.2 events per μb at each momentum setting. The analysis of the film is about 80% finished.

The purpose of the talk is to report on an ongoing effort on a partial wave analysis of the K^-p system around 1 GeV/c. The results are preliminary and the method is our first approximation. I give these warnings because (a) we use a crude momentum dependence for the background amplitudes, namely a linear continuity in momentum is demanded; (b) we fit each channel separately with no attempt, at present, to do an overall fit; and finally, (c) we make no claim to the uniqueness of our fit. We present a fit which makes a certain amount of sense, which has certain apparent difficulties, which will certainly be superseded in further analysis but which serves as a demonstration for the method, our progress and the complexity of the region.

Firstly I would like to show four figures, (Figs. 1 through 4), summarizing the cross section information on the channels I shall discuss, and demonstrating

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the structure in our region. The first slide is the charge exchange cross section from 100 MeV/c - 10 GeV/c. The curves on the bottom axes represent the various resonance contributions as given by the Rosenfeld Tables, the curves through the data represent fits to the data by the various groups responsible for the analysis.

The low energy region has been analysed by Humphrey and Ross, Sakitt et al.[3] Kim[4] and their effective range analysis fit is shown for 0 - ~200 MeV/c. The region about 400 MeV/c has been treated in a partial wave analysis by Watson, Ferro-Luzzi and Tripp[5] in their investigation of the Y_0^* (1520). The curve through the 1 GeV/c region is the results of the preliminary analysis I am reporting. The black points are our data. Sharp and significant structure is observed, in fact it seems to be the dominant structure throughout the entire region shown. Figure 2 gives the elastic scattering cross section over the same region. Again our points are black, and again structure is obvious in the 1 GeV/c region. However, one sees the onset of strong diffraction scattering in the K^-p system soon above the 1 GeV/c region. This renders the channel rather difficult for detailed resonance analysis in this upper region.

Figure 3 shows the sigma-pi cross section - the sum of both charge states - once again the black dots referring to C-H-S data. The sum of the sigma charge states excludes interference between the different I-spin states, thus this slide shows structure from pure I-spin sigma-pi channels. Some structure is surely present in the 1 GeV/c region and indications of possible structure in the lower mass region is present. Finally, in this series, Fig. 4 is of the $\Lambda\pi^0$ cross section which shows the very sharp structure, in this channel, in and above our region. The Y_1^* (1765) is certainly strongly coupled to this $\Lambda\pi$ channel. Thus we may go on to the details of the analysis in the knowledge that we are working in an area where there is strong structure in all the channels we wish to study.

Notice that the plots were against $\sigma/4\pi\lambda^2$, and not σ: this just removes the kinematic or geometrical dependence and leaves the intrinsic momentum dependence of the amplitudes.

The analysis has been performed with the following input:

(a) the two "well-known" resonances,

$$D_{15}\ (1760)$$

$$F_{05}\ (1820)$$

where D and F refer to the angular momentum in the incident K^-p channel, [thus D_{15} means $5/2^-$ state of I-spin 1 (i.e. $T_{I,2J}$)].

(b) We also include three higher resonances, shown by Cool et al.,[6] and Wohl et al.[7]:

Y^* (1915)	The parities of these states have been taken as: (in agreement with Ely et al.[8] and Wohl et al.[7])	F_{15}
Y^* (2040)		F_{17}
Y^* (2100)		G_{07}

(c) We also put in the Y_1^* (1660) in D_{13}.

These resonances are outside the region covered by our data, but they do influence the angular distributions and cross sections within our region. Therefore, they are included with all parameters fixed, where possible.

(d) In addition, in this fit we put resonance states in the D_{03} and D_{05} waves. The analysis requires large contribution in these waves, with considerable momentum dependence. We have therefore parameterized those amplitudes in a resonant form, with a subsequent improvement in the fit. However, no strong claim is made that these states must be resonant. The masses finally come out around 1700 MeV and 1850 MeV, respectively.

(e) The background amplitudes, S_{01}, S_{11}, P_{01}, P_{11}, P_{03} and P_{13} are parameterized in the following way:

$$T = a + b \times \text{Mom}(K^-)$$

where a and b are complex.

We do not insert background amplitudes in those waves which we have taken as resonant.

Each wave is demanded to satisfy unitarity, i.e., the vector must lie inside the unitary circle for the elastic or inelastic channel, whichever is appropriate.

The resonant amplitudes are assumed to have the usual Breit-Wigner form:

$$\upsilon \simeq (I)\, 4\pi\lambda^2 \cdot (J + 1/2) \cdot \left(\frac{\chi\epsilon + \chi}{\epsilon^2 + 1}\right)$$

where

$$\chi = \Gamma_{el} / \Gamma$$

$$\epsilon = 2\,(E - E^*)/\Gamma$$

$$\Gamma = \frac{\cdot B}{B_r}, \quad (B - \text{barrier factor})$$

$$B = \frac{(kr)^{2\ell+1}}{1 + (kr)^{2\ell}}, \quad \text{(really only true for p-wave).}$$

(I) = Isospin Clebsch-Gordan coefficient.

The fit is performed to three channels separately, where the channels are:

1. The elastic channel, which comprises the elastic scattering cross sections and angular distributions, the charge exchange scattering cross sections and angular distributions and the total cross section using the optical theorem, i.e., $4\pi\lambda^2$ Im T - the imaginary part of each scattering amplitude. For the total cross-section data we used our own cross sections† up to the 950 MeV/c region,

† A measurement of the total cross section was performed from a careful scan of about 500 photographs at each momentum, in which all events together with the number of beam tracks and associated δ-rays were recorded. A value of the π and μ contamination (typically less than 5%) was derived for each run by means of the δ-ray count.

(we should now use the good counter total cross section presented at this conference by Bugg), and above that we took the data of Cool et. al.[6], which was better than ours. (We did check that we did agree within our errors.) The errors taken on Cool's measurement were ± 0.5 μb over all points, unless the quoted error was larger.

2. The Sigma-Pi Channel: We fitted the $\Sigma^{\pm}\pi^{\mp}$ cross section and angular distribution.

3. The Lambda-Pi Channel: We fitted the $\Lambda\pi^{0}$ cross sections and angular distributions.

Let's now look at the data and the results of our fit.

I. Fit to Channel I

Figure 5 shows the elastic scattering angular distributions. Here we expand the scattering distribution in a Legendre Polynomial series up to A_6. That is, the angular distribution at each momentum has been fitted to a series of the form:

$$\frac{d\sigma}{d\Omega} = \sum_{0}^{6} A_n P_n (\cos\theta),$$

where P_n $(\cos\theta)$ are the Legendre Polynomials and θ is the scattering angle in the center-of-mass. The fit to the data is fairly good, but the errors are fairly large. In Fig. 6 we have the $\overline{K}^{0}n$ data, again with the fit displayed. We never manage very well above 1.1 GeV/c, even with the inclusion of the higher resonances. Maybe it is also worth noting the difference around the 1820 MeV resonance. The $\overline{K}^{0}n$ data would like this resonance to be sharper than the elastic and total cross-section data will allow. In the next figure, (Fig. 7), we show the total cross section, with the fitted curve from our analysis. We have also plotted the separate contributions from the I-spin 0 and 1 states. (That is, we sum up the coefficients for each isospin state separately and so find 1/2 σ_1 and 1/2 σ_0.)

The σ_0 agrees rather well in shape and magnitude with the data of Bugg et. al.[9], presented earlier. We expect a 4 mb bump at 1700 MeV, while they find (7 - 10) mb bump, but in peak height and the magnitude of the background cross section and for 1820 MeV bump we agree quite well.

Now the overall fit to these data gave a $\chi^2 = 438$, with 37 degree freedom and 345 data points.

II. Fit to Channel II

The sigma angular distribution data are shown in the next two figures (Fig. 8 for the Σ^+). The curve is our fit to the data points, and the dotted part is an extrapolation into the 1660 region (using the 620 MeV/c point of Bastien to anchor the low energy end.) It must be emphasized that we have no data in this region and only continue our calculated amplitudes down into this region, where we have indications of structure in the $\Sigma - \pi$ channel. The fit here is not wonderful, but fair.

The next figure shows the same data for Σ^-. Again we show the low energy extrapolation. These extrapolations for the $\Sigma^{\pm} \pi^{\mp}$ channels show surprising qualitative agreement with the data presented by Rahm et al.,[10] at this Conference. The fit to our data is fairly good. For lack of time we didn't include the polarization of the Σ^+ decay, but we did calculate the predicted polarizations from the best $\Sigma\pi$ fit, and plotted it together with the data. These are shown in Fig. 10. The agreement is surprisingly good. However, it is clear when we include the polarization data the fit parameters will change a little - still it does fit well. We also make low energy polarization predictions, which can be verified by Rahm et. al.[10]

We make one other use of the $\Sigma\pi$ data. We can calculate the predicted $I = 0$ cross section for $\Sigma\pi$ from the best fit amplitudes in $\Sigma^{\pm} \pi^{\mp}$ fit. We may also find the $I = 0$ $\Sigma\pi$ data from our $\Sigma^{\pm}\pi^{\mp}$ mixed I-spin data and the pure $I = 1$ $K^-n \rightarrow \Sigma^-\pi^0$ data which we have from a parallel experiment in deuterium. Thus using the appropriate Clebsch-Gordan coefficients for the subtraction we find the $I = 0$ $\Sigma\pi$ cross section. The next figure, Fig. 11, shows the data, and the prediction. The agreement is really astonishing and shows the 1820 MeV Y_0^* coupling to the $\Sigma\pi$ channel, and also a large enhancement around 1670 MeV. The Willis data, †† I think, will show similar effects in $\Sigma\pi$ channel. This effect comes from the same partial wave which gave rise to the 1700 bump in the total cross section, and K^-p, $\bar{K}^0n$ angular distribution. We are not clear what this means; whether it is the same resonance, or two new states in D_{13} at 1670 MeV and 1705 MeV.

The $\Sigma\pi$ fit may be summarized by very small Y_1^* (1765) coupling, clear evidence at Y_0^* (1820), and some structure in the "background" at around 1660 MeV. The fit parameters were: $\chi^2 = 459$, data = 332, degrees of freedom = 38.

III. Fit to Channel III

Finally, we have the $\Lambda\pi^0$ data,** shown in Fig. 12. This adds very little to the data of Ely et. al.[8], presented earlier, and I won't spend very much time on it.

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†† The Rahm et. al.[10] data (Willis's group) shows structure in the $\Sigma^-\pi^+$ cross section, a 2-1/2 mb. bump, while no corresponding bump is seen in their $\Sigma^+\pi^-$ data. This can only happen if there are two resonances coupled to the $\Sigma\pi$ channel, in the same spin and parity state but with opposite I-spin. Since it is clear that there is an Y_1^* (1660) which is observed in the high energy production experiments, and decays dominantly through Y_0^* (1405) $+\pi$, (which gives the I-spin = 1), and that this has probably spin parity D_{13} (also confirmed in $\Lambda\pi$ channel studies) - it seems plausible that this effect we see in $\Sigma\pi$ is really a $I = 0$, D_{13} resonance around 1670 MeV.

** The technique for choosing $\Lambda\pi^0$ events was to cut at $MM^2 = 2m_\pi$. Here we have no $\Lambda\pi^0\pi^0$ but do have a $\Sigma^0\pi^0$ contamination. Due to phase space at low momenta it gets serious especially when we have a large $\Sigma^0\pi^0$ enhancement at 1660 MeV and indeed, the lower points of our data are always seen to be a bit high.

The next figure (Fig. 13) shows the angular distribution coefficients A_0 through A_6, with our best fit drawn through them. The fit parameters are: $\chi^2 = 344$, data = 165, degrees of freedom = 12.

The parameters from this fit agree well with Ely et. al.[8] data, even in sign of the coupling constants.

The final three figures are displays of the non-resonant background amplitudes. These are shown in the usual circle plots, as Argand diagrams, where one has Re T along, and Im T up. The arrow for the amplitudes refer to its movement from 800 MeV/c to 1200 MeV/c, i.e., the dot is the average value of the amplitude over our region, and the length of the arrow shows the magnitude and direction of its momentum variation. The 400 MeV/c solutions are also shown here as the $\bar{K}$ N. The S-waves are very large and moving fairly slowly. The P_1 waves are also fairly large, with interesting momentum dependence and fairly clear I-spin dependence.

Figure 14 shows the same data for the $\Sigma\pi$ channel, and finally Fig. 15 shows the $\Lambda\pi$ background amplitudes. These are identical to the Ely et. al. amplitudes in phase as well as in magnitude.

Finally, the resonance parameters that derived from this analysis are shown in Table II. The "background" resonances do not behave in a very happy way. There is certainly strong structure in D_{03} amplitude, but with very different masses and width in the $\bar{K}$ N, and π channels. The D_{05} wave has incompatable width estimates in the two channels. However, it should be emphasized here that these effects are interesting, that they point out the complexity of the region, but need a great deal of further study. (One is outside our data region and hopefully the situation will be clarified by Willis, the other is in our data region but doesn't seem to patch up the data it should!)

The two 1 GeV/c resonances appear with much the same parameters we have reported earlier, with perhaps the exception of the 1820 MeV Y_0^* width. (We spoke of this trouble at the beginning of the talk, and seemed to blame the K^-p and σ total data.) The branching ratios are also given.

This analysis will be continued, and hopefully with more work and the help of some new data presented here at this conference, will succeed in describing this very complex region of the K^-p interaction.

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FIGURE CAPTIONS

1. The cross section for the reaction $K^-p \rightarrow \overline{K}^0 n$ from 100 MeV/c to 10 GeV/c. The dotted curves are the predictions of partial wave analysis described in the text, and the solid curves are the expected resonance contributions from the data of Rosenfeld <u>et. al</u>.[11]

2. The cross section for the reaction $K^-p \rightarrow K^-p$, from 100 MeV/c to 20 GeV/c.

3. The cross section for the reaction $K^-p \rightarrow \Sigma^{\pm}\pi^{\mp}$ from 100 MeV/c to 10 GeV/c.

4. The cross section for the reaction $K^-p \rightarrow \Lambda\pi^0$ from 100 MeV/c to 10 GeV/c.

5. The Legendre Polynomial coefficients derived from the differential cross section is $K^-p \rightarrow K^-p$. The dashed curve is the fit from the partial wave analysis described in the text.

6. The Legendre Polynomial coefficients derived from the differential cross section is $K^-p \rightarrow \overline{K}^0 n$. The dashed curve is the fit from the partial wave analysis described in the text.

7. The total K^-p cross section for region (0-1.2) GeV/c. The solid curve is the fit to the data obtained from the partial wave analysis. The dashed lines represent the total cross section in isospin states $I = 0$, and $I = 1$ respectively, also obtained from the phase shift analysis.

8. The Legendre Polynomial coefficients derived from the differential cross section is $K^-p \rightarrow \Sigma^+\pi^-$. The dashed curve is the fit from the partial wave analysis.

9. The Legendre Polynomial coefficients derived from the differential cross section is $K^-p \rightarrow \Sigma^-\pi^+$. The dashed curve is the fit from the partial wave analysis.

10. The polarization of the Σ^+ in the process $K^-p \rightarrow \Sigma^+\pi^-$, as observed by the asymmetry in the decay $\Sigma^+ \rightarrow p\pi^0$. The dashed curves are the polarization

predicted by the partial wave analysis (i.e., this data was not part of the fitted data.)

11. The cross section for the isospin zero $\Sigma\pi$ in region (600 - 1200) MeV/c. The experimental points are described in text, and the dashed curve is the prediction from the partial wave analysis.
12. The Legendre Polynomial coefficients derived from the differential cross sections $K^- p \to \Lambda\pi^0$. The dashed curve is the fit to the data from the partial wave analysis.
13. The non-resonant background amplitudes in the reaction $K^- p \to \bar{K} N$.
14. The non-resonant background amplitudes in the reaction $K^- p \to \Lambda\pi$.
15. The non-resonant background amplitudes in the process $K^- p \to \Sigma\pi$.

TABLE I

LIST OF K^- MOMENTA STUDIED IN THIS EXPERIMENT

Momentum (MeV/c)	Energy in c.m. (MeV)
777	1688
806	1702
838	1718
853	1725
874	1735
894	1745
904	1749
916	1755
935	1764
954	1772
970	1780
991	1791
1022	1805
1044	1814
1061	1822
1080	1831
1102	1841
1117	1847
1130	1853
1153	1863
1169	1871
1185	1879
1226	1897

TABLE II

RESONANCE PARAMETERS FROM THE PARTIAL WAVE FIT

Resonance		Mass	Γ	x_{el}	$x_{\Sigma\pi}$	$x_{\Lambda\pi}$
D_{15}		1770 ± 10	130 ± 20	.44 ± .05	.005 ± .005	.20 ± .05
F_{05}		1820 ± 5	76 ± 10	.60 ± .05	.12 ± .02	--
D_{03}	$\overline{K}N$	1704 ± 10	31 ± 5	.17 ± .05	1 ± .2	--
	$\Sigma\pi$	1665 ± 10	57 ± 10			
D_{05}	$\overline{K}N$	1837 ± 10	78 ± 10	.11 ± .05	.24 ± .05	--
	$\Sigma\pi$	1846 ± 10	156 ± 20			
F_{15}		[1915]	[65]	.06 ± .02	.03 ± .02	.01 ± .01