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K^+p ELASTIC SCATTERING AT 4.6 GeV/c[†]

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ABSTRACT

The elastic scattering of K^+ mesons by protons at 4.6 GeV/c has been studied in a hydrogen bubble chamber experiment. The elastic cross section has been measured and found to be 3.85±0.25 mb. The forward diffraction peak can be adequately fitted by a differential cross section of the form $\frac{d\sigma}{dt} = (\frac{d\sigma}{dt})_o e^{-B|t|}$, where $(\frac{d\sigma}{dt})_o = 16.0\pm1.3$ mb/(GeV/c)^2 and $B = 4.2\pm0.2$ (GeV/c)$^{-2}$. From this fit the magnitude of the ratio of real forward amplitude to imaginary forward amplitude is estimated to be $0.25^{+0.14}_{-0.25}$. Comparison with results of other experiments indicates that B has a momentum dependence extremely similar to that observed in proton-proton elastic scattering.

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1. Introduction

The elastic scattering of positive kaons by protons has been studied over a substantial momentum range. After remaining largely s-wave between 0 and 800 MeV/c[1], it is modified by small p- and d-wave contributions[2] until the onset of substantial inelastic effects at about 1 GeV/c. Above 1.2 GeV/c a large diffractive peak appears which remains a dominant feature at all higher momenta[3]. With only momenta above this diffractive threshold considered, elastic scattering experiments covering the full angular range have been reported at 1.45, 1.96, 3.0, 3.5, 5, and 7.3 GeV/c[4], all from bubble-chamber analyses. Observations of elastic scattering in just the diffraction region $[|t| < 1.2\ (\mathrm{GeV/c})^2]$ by means of a counter experiment have been reported at 6.8, 9.8, 12.8, and 14.8 GeV/c[5]. Interest in the behavior of the differential cross section in the backward direction and its interpretation in terms of u-channel baryon exchange has also stimulated several experiments designed specifically to measure elastic scattering near $\cos\theta = -1$ (ref.[6]).

The general features brought out in these experiments are the following:

(a) Between 1 and 15 GeV/c, the elastic cross section drops monotonically to a near-asymptotic value just above 3 mb.

(b) Extrapolation of the diffraction peak to $t = 0$ leads to forward cross sections in apparent excess of the optical value even at high momenta. The ratios of real to imaginary forward scattering amplitude appear to be somewhat larger than expected from dispersion relations or Regge fits.

(c) There appears to be a significant contribution in the backward direction, in distinction to K^-p experiments at the same momenta, and in agreement with Regge baryon exchange models.

In this paper we report the results of a bubble chamber study of K^+p elastic scattering at 4.6 GeV/c with the statistics of about 4000 events. Our analysis yields results in agreement with (a) and (c) above, but with less real forward amplitude than indicated by some of the other experiments.

2. Experimental Details

The data were obtained from an analysis of about 50 000 photographs of the BNL 80-inch hydrogen bubble chamber in a 4.6-GeV/c electrostatically separated K^+ beam. Approximately 15 000 two-prong events were measured on the LRL Flying-Spot Digitizer (FSD), and remeasured in case of failure on Franckenstein measuring projectors. From these some 4037 elastic scatterings were accepted. A breakdown of the event classes after measurement is given in Table 1. A subsample of the elastic events was checked on the scan table to verify that ionization was compatible with the kinematic fit.

An important source of bias is the loss of events with very small scattering angles and short recoil protons. We have examined this bias by studying the azimuthal distribution of the recoil proton about the incident K^+ line of flight. As a result of this study we have cut out as unreliable the region of $|t| < 0.05$ $(\text{GeV/c})^2$ (recoil proton range < 5 cm), and added a few events in the bins between $|t| = 0.05$ and $|t| = 0.175$ $(\text{GeV/c})^2$. These corrections amounted to about 6% of the population of these bins.

One difficult problem is that of pion contamination, since one cannot kinematically differentiate pion events from kaon events in the forward peak. From considerations of the total cross section given later we estimate an upper limit of about 5% on the pion beam contamination.

3. Results

3.1 Elastic Cross Section

The elastic cross section σ_e was determined from the relation

$$\sigma_e = \left(\frac{\sigma_e}{\sigma_2}\right) \times \left(\frac{\sigma_2}{\sigma_t}\right) \times \sigma_t ,$$

where σ_t = total K^+p cross section,

σ_e/σ_2 = fraction of two-prong events which are elastic scatterings,

σ_2/σ_t = fraction of all K^+p events which are two-prong.

We consider each of these quantities in turn:

(i) σ_e/σ_2

The basic input data have already been given in Table 1. The total number of elastic events is given by 3957 (4 constraints) + 80 (3 constraints) + 633 (correction for short recoils) = 4670. The total number of nonelastic events to be compared with the above number is given by 3034 (1 neutral) + 4208 ($\geq$ 2 neutral) + 128 (zero constraint) = 7370. Thus we get

$$\frac{\sigma_e}{\sigma_2} = \frac{4670}{4670 + 7370} = 0.388\pm0.02 ,$$

where the error comes from a conservative estimate of systematic uncertainties.

(ii) σ_2/σ_t

From a total of 26 552 interactions of all types, some 14 954 two-prong events were found. To these must be added an estimated 824 elastic events with short (and therefore missed) recoils. From these one gets

$$\frac{\sigma_2}{\sigma_t} = \frac{14954 + 824}{26552 + 824} = 0.576\pm0.03 ,$$

where again systematic uncertainties determine the quoted error. By combining (i) and (ii) we find

$$\frac{\sigma_e}{\sigma_t} = 0.388 \times 0.576 = 0.224 \pm 0.014 .$$

(iii) $\underline{\sigma_t}$

The most reliable and precise information on σ_t comes from high-precision counter experiments. By interpolation between the measurements by Bugg et al. and Galbraith et al., we take $\sigma_t = 17.2 \pm 0.2$ mb.† Combining with σ_e/σ_t, we

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†D. V. Bugg et al. [Phys. Rev. 168 (1968) 1466] give $\sigma_t = 17.25 \pm 0.12$ mb at 2.47 GeV/c, whereas W. Galbraith et al. [Phys. Rev. 138 (1965) B913] find an essentially constant value of σ_t of 17.25±0.1 mb above 6 GeV/c. We conclude that 17.2±0.2 mb is an appropriate interpolated value at 4.6 GeV/c and is compatible with other measurements of much poorer accuracy near this momentum.

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obtain $\sigma_e = 3.85 \pm 0.25$ mb.

We have also attempted to check the self-consistency of our data by determining the total cross section from a count of τ ($K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$) decays. The result is 17.2±1.2 mb, in fortuitously good agreement with the counter value. One useful consequence of this result is that it provides a rough estimate of pion contamination. If x is the number of pions for each kaon in the beam, σ_{KM} is our measured kaon total cross section normalized on τ decays, σ_K is the true total kaon cross section, and σ_π is the pion total cross section, one easily shows that x can be estimated from

$$x = \frac{\sigma_{KM} - \sigma_K}{\sigma_\pi} .$$

Taking $\sigma_{KM} = 17.2 \pm 1.2$ mb, $\sigma_K = 17.2 \pm 0.2$ mb, and $\sigma_\pi = 27$ mb[7]),

$$x = 0 \pm 5\% .$$

It is perhaps worth noting that our value of the elastic K^+p cross section is actually insensitive to pion contamination because it is based on a determination of the ratio of elastic to all events, with the normalization being supplied by the known total cross section. Since the ratio of elastic to total cross section for pions is not very different from that for K^+, the influence of a small pion contamination on the value of σ_e is negligible.

3.2 Angular Distribution

The complete center-of-mass angular distribution is shown in Fig. 1. The measured values of $d\sigma/dt$ as a function of $|t|$, the squared momentum transfer, are given in Table 2 and shown, for the forward angles, in Fig. 2. A satisfactory fit of the data between $|t| = 0.05$ and $|t| = 0.8$ $(\text{GeV}/c)^2$ can be made to the form

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_o e^{Bt} .$$

The result is $(d\sigma/dt)_o = 16.0 \pm 1.3$ mb/$(\text{GeV}/c)^2$, $B = 4.2 \pm 0.2$ $(\text{GeV}/c)^{-2}$, where the errors include the systematic uncertainty due to possible pion contamination. The ratio of real to imaginary part of the forward scattering amplitude, α, with 17.2 mb taken as the total K^+p cross section, is

$$|\alpha| = \left|\frac{\text{Rl}\, f(0)}{\text{Im}\, f(0)}\right| = 0.25^{+0.14}_{-0.25} .$$

This result may be compared with the following theoretical expectations: (i) The Regge pole analysis by Dass, Michael, and Phillips[8]) leads to a prediction of $\alpha = -0.4$ at our momentum. (ii) A variety of dispersion relation calculations has given values of α ranging from -0.1 to -0.4 (ref. [9]). It is clear that the errors of our experimental result are too large to permit differentiation between various predictions. It is worth noting, however, that this result appears somewhat smaller and perhaps in better agreement with theoretical expectations than the value $|\alpha| = 0.60\pm0.14$ at 7.3 GeV/c quoted by Chien et al.[4]).

The Regge pole fit of Phillips and Rarita[10]), with the isovector contributions modified to take account of the fit of Rarita and Schwarzschild[11]) to all charge exchange data, is also shown in Fig. 2, and is in good agreement with the data.

As is clear from the distribution shown in Fig. 1, there is a small amount of scattering in the backward direction. The cross section for scattering through c.m. angles greater than 90 deg is 13 ± 4 μb. The corresponding figures for 3.0, 3.5, and 5 GeV/c are 33 ± 10, 24 ± 6, and 8 ± 5 μb respectively[4]). Using only the events from $\cos\theta = -0.92$ to $\cos\theta = -1$, we estimate $\frac{d\sigma}{d\Omega}(180\text{ deg}) = 7^{+5}_{-3}$ μb/sr. A much more precise measurement has been done at 5.2 GeV/c by Baker et al.[6]), with the result $\frac{d\sigma}{d\Omega}(180\text{ deg}) = 10\pm3$ μb/sr. It is interesting to note that a recent analysis of K^-p scattering at 4.6 GeV/c reports no events at angles greater than 90 deg and sets an upper limit to the backward scattering cross section of 2 ± 1 μb[12]). The observed backward scattering in K^+p is generally interpreted in terms of u-channel baryon exchange. Such exchange would, for K^-p, require $S = +1$ baryons, for whose existence there is no clear evidence.

4. Discussion and Comparison with Other Data

We have studied the properties of the forward diffraction peak in K^+p scattering, using both our data and other published information. In order to have some reasonably precise quantities calculated uniformly for all the data, we have made fits at all the momenta to the form

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_0 e^{Bt} , \quad \text{with} \quad 0 < |t| \leq 0.8 \ (\text{GeV/c})^2 .$$

In Fig. 3 we plot the values of B for momenta between 1.2 and 14.8 GeV/c. It is clear that the points follow a smooth curve, and indeed are excellently fitted by the function

$$B = 6.8 \ \beta^2 \ (\text{GeV/c})^{-2} ,$$

where β is the center-of-mass velocity of the K^+p system. There are several interesting remarks to make here:

(a) The proportionality between B and β^2 also occurs in the other well-known case of substantial shrinkage of the diffraction peak with energy, namely proton-proton elastic scattering. Indeed, Krisch[13]) has suggested $\beta^2 P_\perp^2$, where $P_\perp$ is the transverse momentum ($P_\perp^2 \approx |t|$ at high energy) as a universal variable in terms of which p-p angular distributions can be represented. In p-p scattering the coefficient of proportionality B/β^2 is larger, namely about 10 $(\text{GeV/c})^{-2}$ instead of 6.8 $(\text{GeV/c})^{-2}$. This similarity to the p-p interaction is but one of many, including the absence of resonances and close resemblance in the momentum dependence of elastic and inelastic cross sections.

(b) The asymptotic value of B (assuming that this has meaning--that is, that the Pomeranchuk trajectory is flat) is 6.8 $(\text{GeV/c})^{-2}$. It should be noted that for K^-p the value of B changes very little with momentum and appears to have, when fitted over the same range of $|t|$, a value[14]) of 7.1 to 7.2 $(\text{GeV/c})^{-2}$. Thus the K^+ and K^- scattering in the diffraction peak do become nearly identical at high momentum, although very different at low momenta. This value of B is also in good agreement with the value obtained in pion elastic scattering, again almost independently of incident momentum.

(c) If we assume that asymptotically (i) the real part of the forward scattering amplitude goes to zero, (ii) the total cross section remains at 17.2 mb, (iii) the linear exponential remains a good representation of the angular distribution from $t = 0$ to at least $|t| \gtrsim 0.6\ (\mathrm{GeV}/c)^2$, the elastic cross section σ_e has the asymptotic value of 2.2 mb, and the ratio σ_e/σ_t has the limit 0.13. Both of these figures are substantially lower than those at the highest measured momentum of 14.8 GeV/c, $\sigma_e = 3.41 \pm 0.17$ mb, $\sigma_e/\sigma_t = 0.20$ (ref.[5])). However, it is interesting to note that for K^-p at 10 GeV/c, with $\sigma_e = 3.20 \pm 0.14$ mb, $\sigma_t = 22.5 \pm 0.2$ mb, the value of σ_e/σ_t, namely 0.142 ± 0.006 (ref. [14])), is close to the above asymptotic limit.

We now consider briefly the phase of the forward K^+p amplitude. For all momenta at which measurements have been made the forward cross section $(d\sigma/dt)_0$ always lies substantially higher than the optical value. In fact, as indicated earlier, both dispersion-relation calculations and Regge-model predictions lead one to expect a substantial ratio of real to imaginary forward amplitudes, decreasing in magnitude with increasing momentum. The experimental data do not exhibit any clear trend with changing momentum except the existence of a sizable real part for the forward amplitude. More precise data are clearly required to study this question, particularly since the possible presence of a significant spin-flip term may make the usual extrapolations to $t = 0$ somewhat uncertain.

We thank the Brookhaven 80-inch bubble chamber staff for help with the exposure. We also acknowledge the support of our Scanning and Programming Groups, and the Data Handling Group under Howard White. We have benefited from discussions with Gerson Goldhaber and from calculations made by Henry Tanz.

Table 1. Breakdown of accepted two-prong measurements

Elastic scattering events with 4 constraints	3 957
Elastic scattering events with 3 constraints	80
Events with one missing neutral	3 034
Events with two or more missing neutrals	4 208
Inelastic events in which a constraint is dropped	128
Total accepted	11 407

Table 2. Angular distribution for K^+p elastic scattering

$\lvert t\rvert$ $(GeV/c)^2$	Average value of cos θ	$d\sigma/dt$ $\left(\frac{mb}{(GeV/c)^2}\right)$	N_{corr}	$\lvert t\rvert$ $(GeV/c)^2$	Average value of cos θ	$d\sigma/dt$ $\left(\frac{mb}{(GeV/c)^2}\right)$	N_{corr}
0.050-0.075	0.9835	13.20±1.08	400	0.725-0.750	0.8059	0.56±0.14	17
0.075-0.100	0.9770	11.91±1.00	361	0.750-0.775	0.7993	0.56±0.14	17
0.100-0.125	0.9704	9.50±0.83	288	0.775-0.800	0.7927	0.46±0.13	14
0.125-0.150	0.9638	8.38±0.76	254	0.800-0.825	0.7861	0.56±0.14	17
0.150-0.175	0.9572	8.05±0.73	244	0.825-0.850	0.7795	0.66±0.15	20
0.175-0.200	0.9506	6.30±0.61	191	0.850-0.875	0.7730	0.36±0.11	11
0.200-0.225	0.9441	6.83±0.65	207	0.875-0.900	0.7664	0.46±0.13	14
0.225-0.250	0.9375	6.57±0.63	199	0.900-0.925	0.7598	0.26±0.09	8
0.250-0.275	0.9311	5.71±0.57	173	0.925-0.950	0.7532	0.36±0.11	11
0.275-0.300	0.9243	5.02±0.52	152	0.950-0.975	0.7466	0.20±0.08	6
0.300-0.325	0.9177	3.80±0.43	115	0.975-1.000	0.7401	0.40±0.12	12
0.325-0.350	0.9112	3.50±0.41	106	1.0-1.1	0.7236	0.27±0.05	33
0.350-0.375	0.9046	3.14±0.38	95	1.1-1.2	0.6973	0.17±0.04	20
0.375-0.400	0.8980	3.37±0.40	102	1.2-1.3	0.6710	0.11±0.03	13
0.400-0.425	0.8914	2.90±0.36	88	1.3-1.4	0.6446	0.033±0.02	4
0.425-0.450	0.8848	2.51±0.33	76	1.4-1.5	0.6183	0.041±0.02	5
0.450-0.475	0.8783	2.48±0.33	75	1.5-1.6	0.5920	0.033±0.02	4
0.475-0.500	0.8717	2.18±0.30	66	1.6-1.7	0.5657	0.016±0.01	2
0.500-0.525	0.8651	1.95±0.28	59	1.7-1.8	0.5394	0.024±0.01	3
0.525-0.550	0.8585	1.75±0.27	53	1.8-1.9	0.5130	0.008±0.01	1
0.550-0.575	0.8519	1.39±0.23	42	1.9-2.0	0.4867	0.008±0.01	1
0.575-0.600	0.8454	1.19±0.21	36	2.0-3.0	0.3419	0.002±0.001	2
0.600-0.625	0.8388	1.29±0.22	39	3.0-4.0	0.0787	0.002±0.001	3
0.625-0.650	0.8322	1.09±0.20	33	4.0-5.0	-0.1845	0.001±0.001	1
0.650-0.675	0.8256	0.83±0.17	25	5.0-6.0	-0.4477	0.002±0.001	3
0.675-0.700	0.8190	1.02±0.20	31	6.0-7.0	-0.7110	0.005±0.002	6
0.700-0.725	0.8126	0.96±0.19	29	7.0-7.6	-0.9213	0.007±0.003	5

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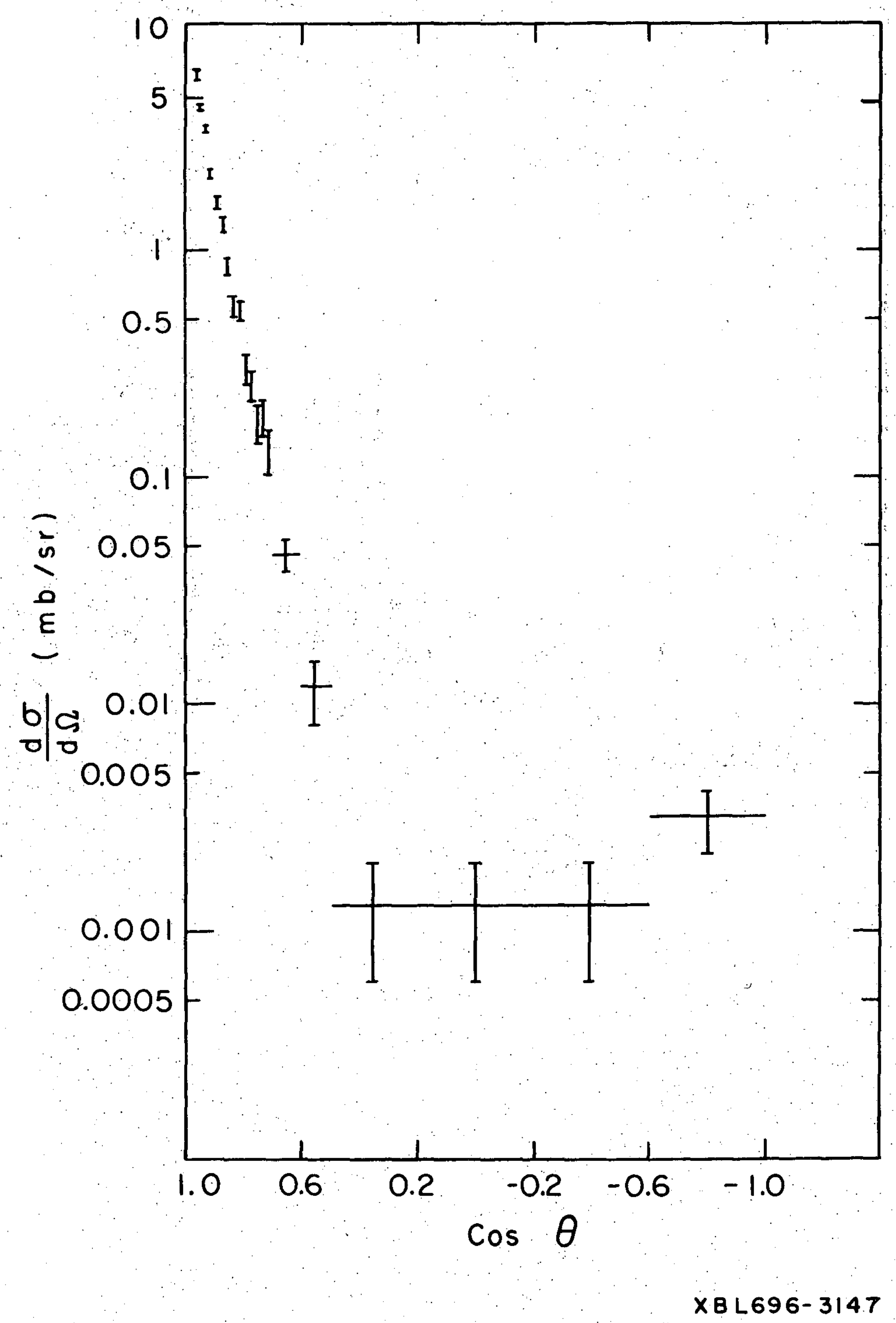
FIGURE CAPTIONS

Fig. 1. Differential cross section, $d\sigma/d\Omega$, for K^+p elastic scattering at 4.6 GeV/c.

Fig. 2. Differential cross section in terms of momentum transfer squared for forward angles. The solid curve is derived from the Regge fit discussed in the text.

Fig. 3. Momentum dependence of the parameter B in the fit to the diffraction region of the form e^{Bt}. The solid curve is the function $6.8\ \beta^2\ (\mathrm{GeV}/c)^{-2}$.


10
5
1
0.5
0.1
0.05
0.01
0.005
0.001
0.0005
dσ/dΩ (mb/sr)
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0.6
0.2
-0.2
-0.6
-1.0
Cos θ
XBL696-3147

Fig. 1

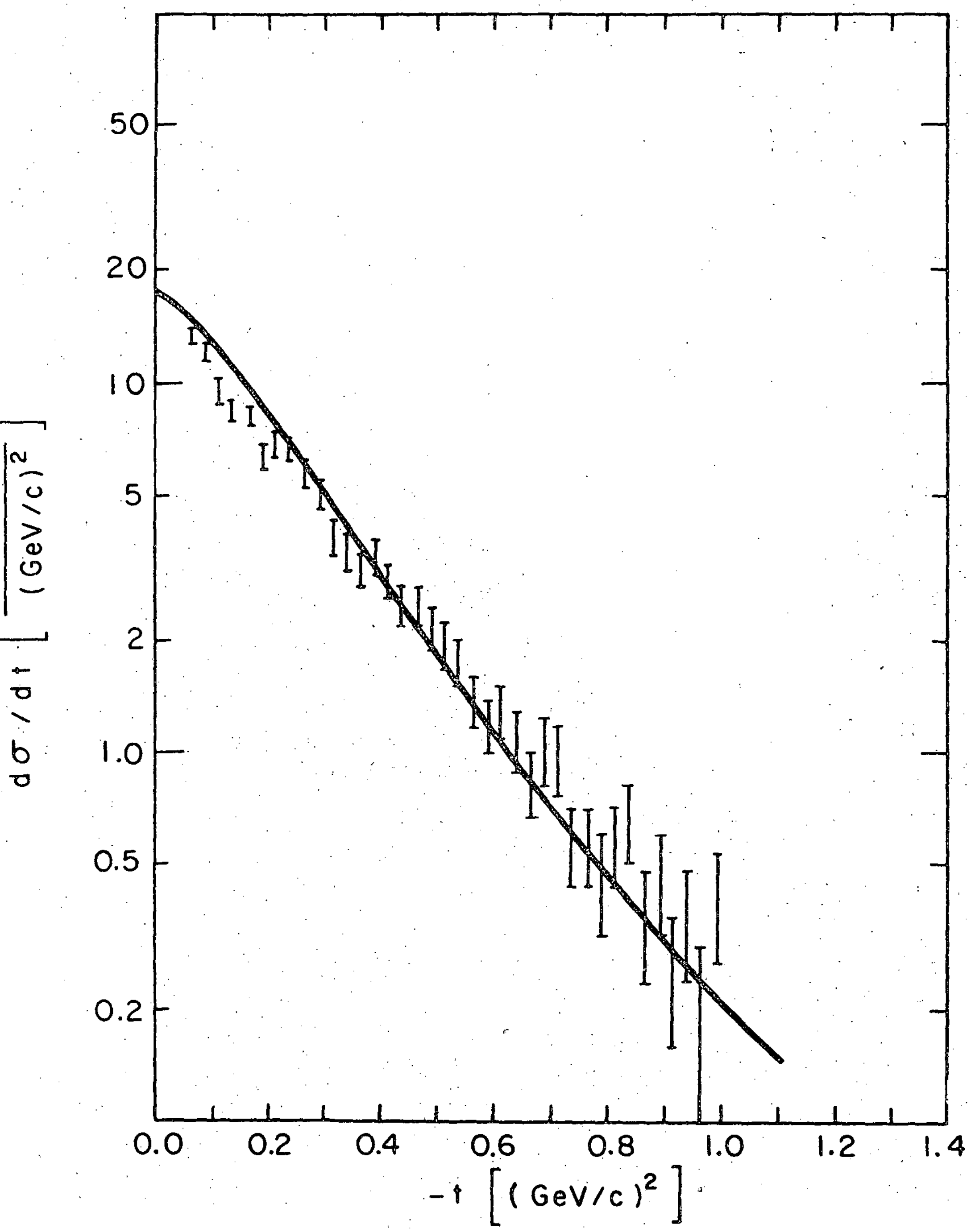

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Fig. 2

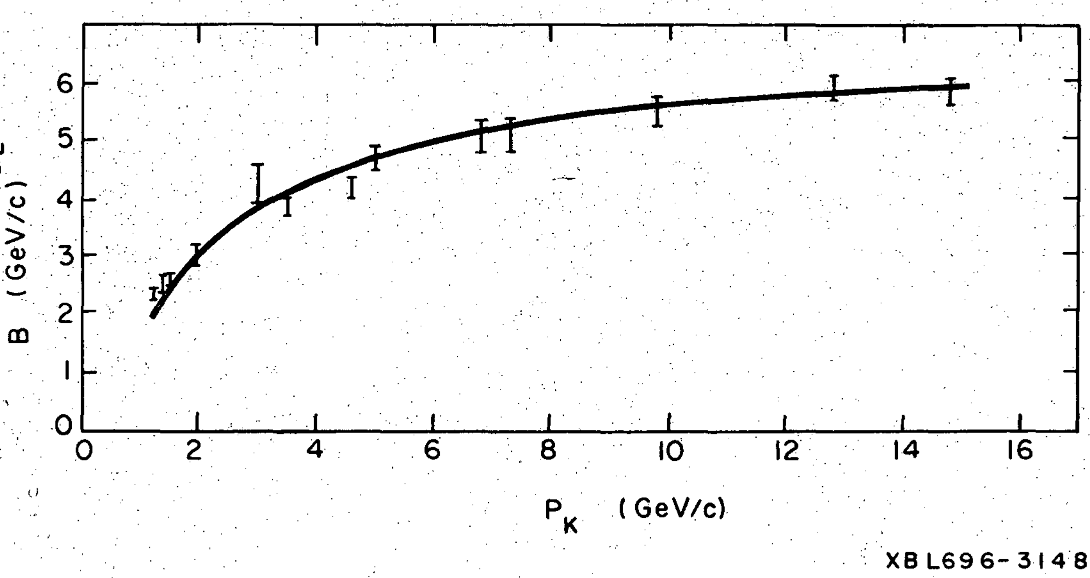

Fig. 3

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