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THE REACTION $K_L^o p \to K_S^o p$ FROM 1.3 TO 8.0 GeV/c *

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ABSTRACT

Total and differential cross sections are presented for the reaction $K_L^o p \to K_S^o p$ from 1.3 to 8.0 GeV/c as measured in an exposure of the SLAC 40-inch hydrogen bubble chamber to a neutral beam. The forward points of $\frac{d\sigma}{dt}(K_L^o p \to K_S^o p)$ together with K^+n and K^-n total cross sections are used to determine the intercept of the effective Regge trajectory, $\alpha(0) = 0.47 \pm 0.09$, and the regeneration phase, $\phi_f = -43^o \pm 8^o$.

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We present experimental results on the reaction

$$K_L^o p \to K_S^o p \tag{1}$$

covering the momentum interval from 1.3 to 8.0 GeV/c. Previous investigations of reaction (1) have been reported by Firestone et al.[1] in a hydrogen bubble chamber experiment and by Darriulat et al.[2] in a transmission regeneration experiment.

In the t channel, the reaction must proceed through exchange of neutral mesons having natural spin parity and odd charge conjugation. The only known candidates are the members of the vector nonet (ρ, ω, and ϕ). As pointed out by Gilman,[3] ω exchange is expected to dominate over ρ in the forward direction and ϕ exchange is expected to be negligible due to the experimentally small $\phi\bar{N}N$ coupling. The s and t behavior of the cross section and the phase of the forward amplitude are therefore powerful tools in understanding the properties of ω exchange. A more complete analysis of these exchanges is given in the following letter.[4]

The results presented for reaction (1) are based on an analysis of 200,000 photographs from a total exposure of 800,000 photographs of $K_L^o p$ interactions in the SLAC 40-inch hydrogen bubble chamber. The details of the beam and the K_L^o momentum spectrum are given elsewhere.[5] We have checked carefully for possible systematic uncertainties in our determination of the K_L^o momentum spectrum and conclude that they are negligible compared to the statistical errors of our data sample. The events were found in a scan of the one-prong-plus-vee topology, measured on conventional film plane machines, and reconstructed and fitted with the TVGP-SQUAW computer programs. The sample consists of 571 events in the momentum interval 1.3 to 8.0 GeV/c of which less than 1% are kinematically ambiguous with other hypotheses.[6] Corrections have been applied for scanning inefficiencies due to K^o lifetime and steeply dipping protons.

The cross section for reaction (1) as a function of K_L^o laboratory momentum is presented in Fig. 1 and Table I. As indicated by the solid line, the data are well described by the empirical law, $\sigma \sim p_{LAB}^{-n}$, with $n = 2.1 \pm 0.2$, a value typical of many inelastic meson exchange reactions.

The differential cross section, averaged over three momentum intervals, is presented in Table II and illustrated in Fig. 2a. The main features are a sharp forward peak with an average slope of $10 \pm 2\ \mathrm{GeV}^{-2}$, a distinct shoulder in the interval $0.3 \leq |t| \leq 0.7\ \mathrm{GeV}^2$, and a rapid fall off for t greater than $1.0\ \mathrm{GeV}^2$. The differential cross section is observed to fall as p_{LAB}^{-1} in the forward direction and as $p_{LAB}^{-2.5}$ for $|t| \sim 1\ \mathrm{GeV}^2$.

The intercept of $d\sigma/dt$ at t=0 has been determined in a smooth way over the entire energy interval by a fit to the forward data points using an empirical function of the form:

$$\frac{d\sigma}{dt}(s) \propto s^{-m} \exp\left\{\left[b + c\,\ln(s/s_0)\right] t\right\} \qquad (2)$$

where m, b, and c are fitted parameters and $s_0 = 1\ \mathrm{GeV}^2$. In Fig. 2b the differential cross section for the forward region is shown in small t intervals together with the results of the fit. The values of the parameters are $m = 1.3 \pm 0.3$, $b = 5.5 \pm 2.0\ \mathrm{GeV}^{-2}$, and $c = 2.0 \pm 1.5\ \mathrm{GeV}^{-2}$. The parameter c indicates shrinkage of the forward peak as the slope varies from 8.7 to 11.0 GeV^{-2} over the momentum range from 2.0 to 8.0 GeV/c. The values obtained for $(d\sigma/dt)_{t=0}$ as a function of p_{LAB} are shown in Fig. 3 by the solid curve with the experimental corridor of uncertainty represented by the two dashed curves. For comparison, the values reported recently by Ref. 2 are also shown and agree well with the present experiment.

The ratio of the real to imaginary part and the phase of $A(K_L^o p \to K_S^o p)$, the forward amplitude, are given by:

$$\left|\frac{\mathrm{Re}A}{\mathrm{Im}A}\right| = \left\{\left[\left(\frac{d\sigma}{dt}\right)_{t=0} \Big/ \left(\frac{d\sigma}{dt}\right)_{OPT}\right] - 1\right\}^{1/2}, \qquad (3)$$

and

$$\phi = \tan^{-1}\left[\mathrm{ImA}/\mathrm{ReA}\right] .$$

The optical point is given by

$$\left(\frac{d\sigma}{dt}\right)_{OPT} = \frac{\pi}{k^2}\,|\mathrm{ImA}|^2 \tag{4}$$

where k is the center of mass momentum and where, from isospin invariance and the optical theorem,

$$\mathrm{ImA}(K_L^o p \to K_S^o p) = \frac{k}{8\pi}\left[\sigma_T(K^+n) - \sigma_T(K^-n)\right] \tag{5}$$

In Fig. 3, the values for the optical point computed from total cross section data[7-9] and multiplied by a factor of two are compared with our measured $(d\sigma/dt)_{t=0}$. The ratio of the real to imaginary part of A is near unity over the entire energy range as summarized in Table III.

The quadrant ambiguity for ϕ may be resolved by noting first that the experimental cross sections in Eq. (5) imply that ImA < 0. In addition, Regge theory gives the relation

$$\mathrm{ReA}/\mathrm{ImA} = \tan\left[\frac{1}{2}\,\pi\alpha(0)\right] \tag{6}$$

where $\alpha(0)$ is the effective trajectory intercept. For any reasonable trajectory the intercept should be between 0 and 1, which implies ReA/ImA > 0. To satisfy these two relations ϕ must lie in the third quadrant. The values of ϕ, given in Table III, are consistent with being constant from 1.3 to 8.0 GeV/c.[10] The weighted average over this energy range is

$$\phi = -133^o \pm 8^o .$$

The values of the trajectory intercept calculated from Eq. (6) are also presented in Table III and give an average value

$$\alpha(0) = 0.47 \pm 0.09 .$$

If ω exchange is assumed to dominate the forward amplitude, $\alpha(0)$ may be identified with the ω trajectory intercept. The above value is higher than those obtained in previous phenomenological Regge fits[11] but is consistent with a linear trajectory of unit slope passing through the physical ω mass. It should be noted that the ρ contribution has been ignored in determining the intercept because it is expected to be less than a 20% effect.[3]

The regeneration phase for hydrogen, ϕ_f, is defined by

$$\phi_f = \arg\left\{ i\,A(K_L^o p \rightarrow K_S^o p)_{t=0} \right\} = \phi + \frac{\pi}{2}$$

Thus, we find for an average value

$$\phi_f = -43^o \pm 8^o \ ,$$

which may be compared with the experimental result of Ref. 2 for hydrogen ($-42^o \pm 17^o$), and also with the results for copper[12] ($-45.2^o \pm 7.3^o$) and for carbon[13] ($-37^o \pm 10^o$). Within the errors, the regeneration phase for hydrogen is the same as for heavy nuclei in agreement with recent optical model calculations.[14]

In summary, we find the main features of the reaction $K_L^o p \rightarrow K_S^o p$ in the momentum range 1.3 to 8.0 GeV/c to be the following:

1. The cross section σ falls as $(p_{LAB})^{-n}$, with $n = 2.1 \pm 0.2$;
2. The forward differential cross section, $(d\sigma/dt)_{t=0}$, falls as $(p_{LAB})^{-m}$, with $m = 1.3 \pm 0.3$;
3. The ratio of the real to imaginary part of the forward amplitude is consistent with unity over the entire energy region, with an average value of 0.82 ± 0.20;
4. The average values of ϕ, the phase of the forward amplitude, and ϕ_f, the regeneration phase, are $-133^o \pm 8^o$ and $-43^o \pm 8^o$, respectively;
5. If the reaction is assumed to be dominated in the forward direction by Reggeized ω exchange, then the average value of the trajectory intercept, $\alpha_\omega(0)$, is 0.47 ± 0.09.

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2. P. Darriulat et al., Phys. Letters 33B, 433 (1970).
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6. In addition, we have considered such processes as $K_L^o p$ elastic scattering followed by K_S^o regeneration or by the CP violating K_L^o decay ($K_L^o \rightarrow \pi^+\pi^-$), or K_S^o regeneration followed by $K_S^o p$ elastic scattering. We estimate these processes to have a combined effect smaller than 1% for our data.
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FIGURE CAPTIONS

1. Cross section for $K_L^o p \to K_S^o p$ versus p_{LAB}. The solid line corresponds to $\sigma \propto p_{LAB}^{-n}$, with $n = 2.1 \pm 0.2$.

2. Differential cross sections for $K_L^o p \to K_S^o p$. The data are averaged over three momentum intervals: $1.3 \leq p_{LAB} \leq 2.0$ GeV/c (♦); $2.0 \leq p_{LAB} \leq 4.0$ GeV/c (♦); $4.0 \leq p_{LAB} \leq 8.0$ GeV/c (▲). (a) Full t region. Note the breaks in the ordinate scale as indicated by the shaded area. (b) Small t region. The curves result from a fit used to determine $(d\sigma/dt)_{t=0}$ (see text).

3. Forward differential cross section for $K_L^o p$ - $K_S^o p$. The data are summarized by the smooth curve and the uncertainties by the dashed curves. For comparison, we show the results of Ref. 2 (♦) and the optical points (multiplied by a factor of two) calculated from the total cross sections of Refs. 7 - 9 (♦).

TABLE I

$K_L^o p \rightarrow K_S^o p$ Cross Sections

p_{LAB} (GeV/c)	Events	σ (μb)
1.3 - 1.6	74	627 ± 80
1.6 - 1.8	75	722 ± 85
1.8 - 2.0	49	411 ± 60
2.0 - 2.2	57	420 ± 55
2.2 - 2.4	38	277 ± 45
2.4 - 2.6	44	287 ± 45
2.6 - 2.8	40	250 ± 40
2.8 - 3.0	27	171 ± 35
3.0 - 3.4	45	146 ± 22
3.4 - 3.8	23	86 ± 18
3.8 - 4.2	31	115 ± 21
4.2 - 5.0	34	77 ± 14
5.0 - 6.0	21	54 ± 12
6.0 - 8.0	13	28 ± 8

TABLE II

$K_L^o p \rightarrow K_S^o p$ Differential Cross Sections

<table>
<tr><th rowspan="3">-t
(GeV^2)</th><th colspan="6">p_{LAB} (GeV/c)</th></tr>
<tr><th colspan="2">1.3 - 2.0</th><th colspan="2">2.0 - 4.0</th><th colspan="2">4.0 - 8.0</th></tr>
<tr><th>Events</th><th>$d\sigma/dt$
($\mu b/GeV^2$)</th><th>Events</th><th>$d\sigma/dt$
($\mu b/GeV^2$)</th><th>Events</th><th>$d\sigma/dt$
($\mu b/GeV^2$)</th></tr>
<tr><td>0.05 - 0.1</td><td>10</td><td>660 ± 210</td><td>25</td><td>368 ± 75</td><td>17</td><td>177 ± 43</td></tr>
<tr><td>0.1 - 0.2</td><td>16</td><td>443 ± 110</td><td>32</td><td>196 ± 35</td><td>17</td><td>73 ± 18</td></tr>
<tr><td>0.2 - 0.3</td><td>8</td><td>241 ± 85</td><td>18</td><td>107 ± 25</td><td>8</td><td>35 ± 12</td></tr>
<tr><td>0.3 - 0.4</td><td>11</td><td>296 ± 96</td><td>19</td><td>112 ± 26</td><td>7</td><td>32 ± 12</td></tr>
<tr><td>0.4 - 0.5</td><td>10</td><td>258 ± 82</td><td>18</td><td>107 ± 25</td><td rowspan="2">6</td><td rowspan="2">16 ± 7</td></tr>
<tr><td>0.5 - 0.6</td><td>17</td><td>517 ± 125</td><td>12</td><td>73 ± 21</td></tr>
<tr><td>0.6 - 0.7</td><td>11</td><td>273 ± 83</td><td>20</td><td>123 ± 28</td><td rowspan="2">10</td><td rowspan="2">19 ± 6</td></tr>
<tr><td>0.7 - 0.8</td><td>16</td><td>378 ± 95</td><td>14</td><td>89 ± 24</td></tr>
<tr><td>0.8 - 1.0</td><td>15</td><td>172 ± 45</td><td>25</td><td>71 ± 15</td><td rowspan="2">11</td><td rowspan="2">10.7 ± 3.2</td></tr>
<tr><td>1.0 - 1.2</td><td>15</td><td>215 ± 55</td><td>17</td><td>47 ± 12</td></tr>
<tr><td>1.2 - 1.4</td><td>11</td><td>147 ± 44</td><td>11</td><td>33 ± 10</td><td rowspan="3">2</td><td rowspan="3">1.0 ± 1.0</td></tr>
<tr><td>1.4 - 1.6</td><td>19</td><td>332 ± 76</td><td rowspan="2">11</td><td rowspan="2">16 ± 4</td></tr>
<tr><td>1.6 - 1.8</td><td>12</td><td>188 ± 54</td></tr>
</table>

TABLE III

FORWARD AMPLITUDE RESULTS FOR $K_L^o p \rightarrow K_S^o p$

p_{LAB} [a] (GeV/c)	$\left(\frac{d\sigma}{dt}\right)_0$ (mb/GeV^2)	$\left(\frac{d\sigma}{dt}\right)_{OPT}$ (mb/GeV^2)	$\left\lvert\frac{ReA}{ImA}\right\rvert$	ϕ (Degrees)	$\alpha(0)$
1.3 - 2.0	1.31 ± 0.40	0.73 ± 0.05 [b]	0.89 ± 0.36	-132 ± 14	0.46 ± 0.16
2.0 - 3.3	0.85 ± 0.20	0.52 ± 0.06 [b]	0.79 ± 0.31	-129 ± 13	0.43 ± 0.14
6.0	0.34 ± 0.10	0.24 ± 0.07 [c]	0.64 ± 0.43	-123 ± 18	0.36 ± 0.20
8.0	0.24 ± 0.09	0.06 ± 0.03 [c]	1.83 ± 1.17	-152 ± 19	0.68 ± 0.21
WEIGHTED AVERAGES			0.82 ± 0.20	-133 ± 8	0.47 ± 0.09

a. Momentum values chosen to correspond to available $\sigma_T(K^{\pm}n)$ data.

b. Calculated from the cross sections of Refs. 8 - 9. We have estimated the overall systematic uncertainty in $\sigma_T(K^{\pm}n)$ as 2%. This estimate includes a 1% contribution for nuclear screening. Corrections for Fermi motion are not important for this comparison because wide intervals of momentum have been used.

c. Calculated from the cross sections of Ref. 7.

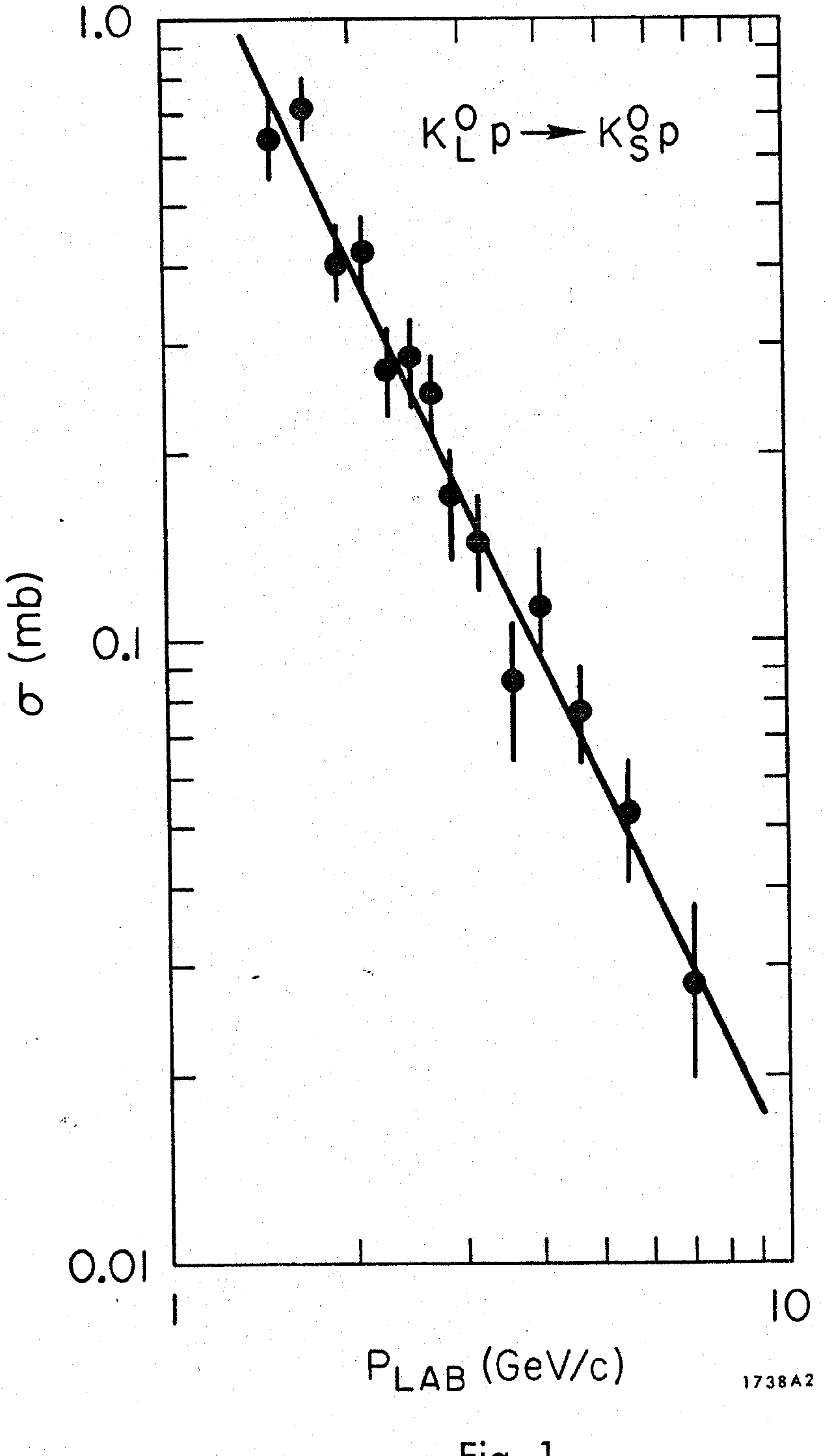


Fig. 1

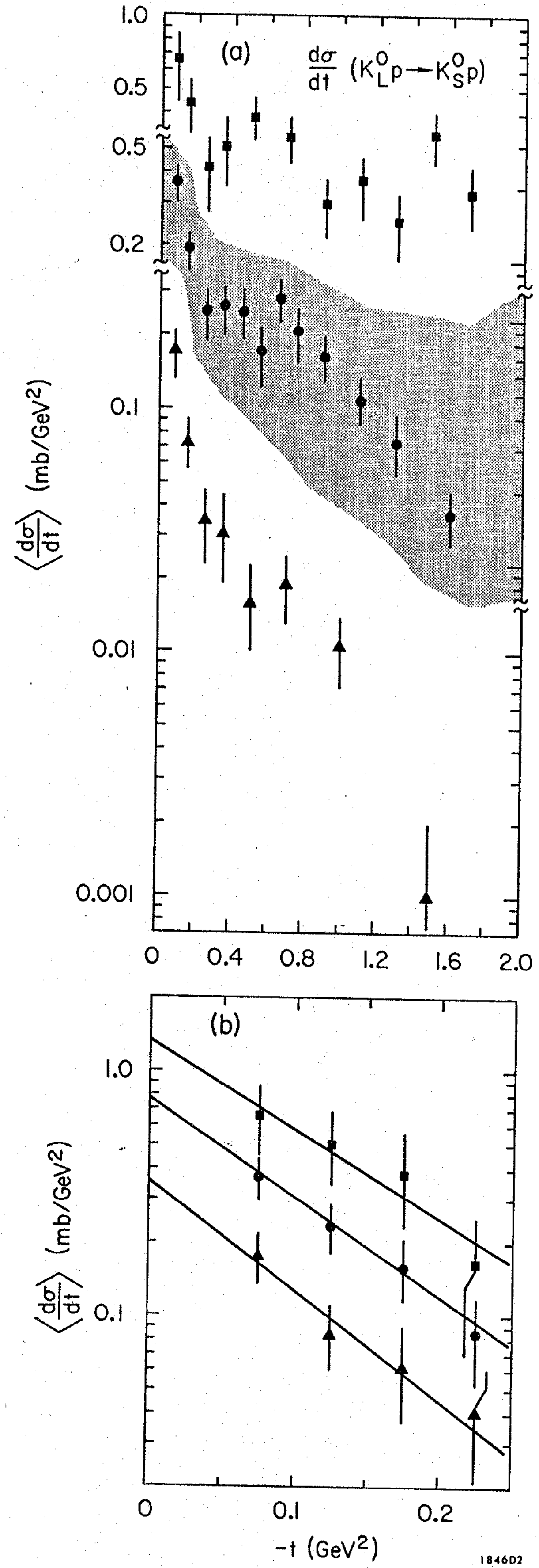
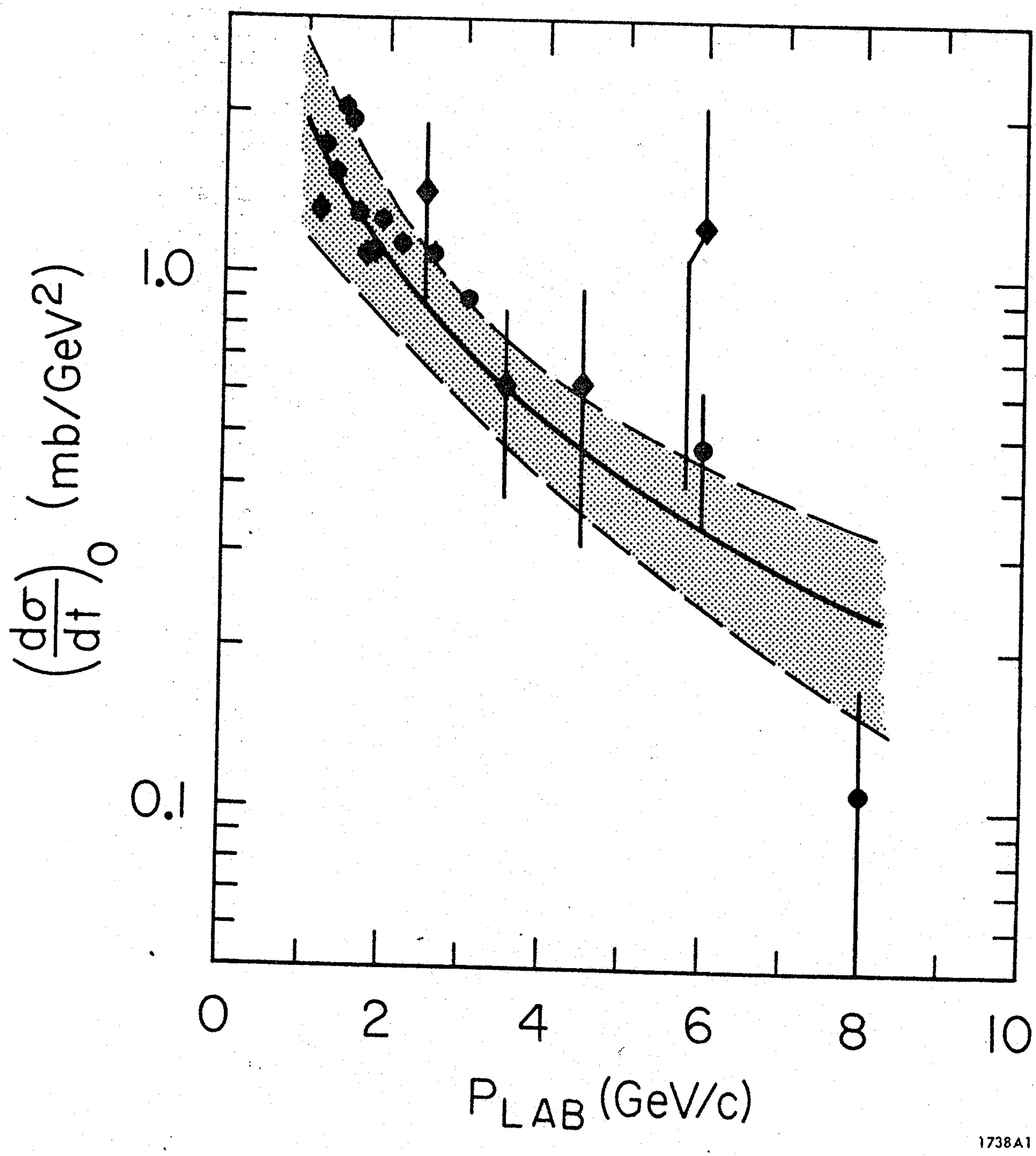

(a)
$\frac{d\sigma}{dt}$ ($K_L^0 p \rightarrow K_S^0 p$)
1.0
0.5
0.5
0.2
0.1
0.01
0.001
$\langle \frac{d\sigma}{dt} \rangle$ (mb/GeV^2)
0
0.4
0.8
1.2
1.6
2.0
(b)
1.0
0.1
$\langle \frac{d\sigma}{dt} \rangle$ (mb/GeV^2)
0
0.1
0.2
$-t$ (GeV^2)
1846D2

Fig. 2



1.0
0.1
$\left(\frac{d\sigma}{dt}\right)_0$ (mb/GeV^2)
0
2
4
6
8
10
P_{LAB} (GeV/c)
1738A1

Fig. 3