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PHOTOPRODUCTION OF K^+-HYPERON FROM HYDROGEN AND DEUTERIUM AT 11 GEV[*]

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ERRATA

on page 6, line 9: change ±0.05 to ±0.12.

on page 8, line 5 of Reference 6: 0.30 ±0.11 ±0.05 should be changed to read 0.30 ±0.11 ±0.12.

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[*] Work supported by the U. S. Atomic Energy Commission.

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ABSTRACT

Using an 11-GeV bremsstrahlung beam and the SLAC 20-GeV spectrometer, we have measured K^+ missing mass spectra from hydrogen and deuterium at five angles with momentum transfer squared ranging from 0.025 to 0.46 GeV^2. Steps in the spectra as a function of missing mass were found corresponding to production of Λ, Σ, $\Sigma_{1385} + \Lambda_{1405}$, and Λ_{1520}. The ratio of Σ^- to Σ^o production is not consistent with pure isotopic spin 1/2 in the t-channel for the reaction $\gamma N \rightarrow K^+\Sigma$. The cross sections for $\gamma N \rightarrow K^+\Sigma_{1385}$ compared with $\gamma N \rightarrow \pi\Delta$ violate an SU(3) prediction.

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The differential cross section for $\gamma p \rightarrow K^+\Lambda$, $\gamma p \rightarrow K^+\Sigma^o$, $\gamma p \rightarrow K^+(\Sigma^o_{1385} + \Lambda^o_{1405})$, $\gamma p \rightarrow K^+\Lambda_{1520}$, $\gamma n \rightarrow K^+\Sigma^-$, and $\gamma n \rightarrow K^+\Sigma^-_{1385}$ have been measured at a photon energy of 11 GeV for forward K^+ angles. The method and apparatus used are similar to that used previously to measure single π and K photoproduction.[1] An 11-GeV bremsstrahlung beam passing through a 27-cm liquid hydrogen or liquid deuterium target produced K^+ mesons which were detected in the SLAC 20-GeV spectrometer. Particle detectors included two Čerenkov counters, a shower counter, and range counters to separate K^+ mesons from pions, protons, positrons, and muons. The spectrometer acceptance was divided into 20 missing mass bins by use of scintillation counter hodoscopes. To obtain data over a range of missing mass and to average out systematic errors in the relative solid angles of the mass bins, the data were accumulated by a series of many runs with a central spectrometer momentum spacing of one bin width. In this way, data points in the missing mass spectrum could be accumulated having an equal contribution from each hodoscope bin. For each event, the missing mass was calculated using the end point of the bremsstrahlung E_0 as the photon energy. An event will therefore be tabulated at a mass greater than the actual mass produced in the reaction by an amount proportional to $E_0 - k$, where k is the actual photon energy. The yield thus obtained then has steps, reflecting the bremsstrahlung spectrum shape, at missing mass values corresponding to particles produced in association with the detected K^+.

A spectrum obtained from hydrogen with empty target subtracted is shown in Fig. 1b. Fits to the missing mass spectra were made, using the sum of phase space and four steps. The relative positions of the steps were fixed from the known masses of the Λ, Σ, Λ_{1520}, and the average mass of Σ_{1385} and Λ_{1405}. The Σ_{1385} and Λ_{1405} are not resolved due to their natural widths ($\Gamma = 40$ MeV) and the experimental mass resolution (Gaussian with $\sigma = 22 \pm 3$ MeV). The steepness of the steps was adjusted to correspond to the combined effects of our experimental resolution and the natural widths of the resonances. The absolute calibration of the missing mass scale as well as the resolution was determined from the step in the reaction $\gamma p \rightarrow \pi^+ n$ measured at the same time. Because the missing mass spectra were taken at a constant laboratory angle, t varies with missing mass or photon energy for each step. The t dependence of the cross sections was therefore used to calculate the proper shapes for the steps. Fig. 1a is a derivative spectrum of 1b with smoothing applied to the data.[2] It illustrates what would be measured with a monochromatic photon beam. Because there are numerous known resonances at the higher masses, only the data below $M_x^2 = 2.5$ GeV^2 were used to obtain cross sections. Fits were also made replacing phase space by a polynomial with linear and quadratic terms in M_x^2. These fits gave cross sections differing from those obtained with phase space as background by less than the statistical errors.

Because of the Fermi motion, steps obtained in the missing mass spectrum from deuterium are somewhat smeared out. The detailed shape of the steps used to fit the deuterium spectrum was calculated using the Hulthén wave function,

$$H(P_s) = C P_s^2 \left[\frac{1}{P_s^2 + \alpha^2} - \frac{1}{P_s^2 + (\alpha + \mu)^2} \right]^2$$

where P_s is the spectator nucleons momentum, $\alpha = 0.0457$ GeV and $\mu = 0.214$ GeV are parameters as determined by White et al.,[3] and C is a constant to properly normalize $H(P_s)$. Variations in the magnitude of α and μ of 10% caused changes in measured cross sections for Λ and Σ of less than 2% and in all cases changes are negligible compared to the statistical errors. The Fermi smearing has a small effect for small t, but is quite serious for the points at larger t and results in large statistical errors including correlation errors between the different steps and the background (phase space or polynomial).

Cross sections obtained from the hydrogen data are shown in Table I and Fig. 2. Only statistical errors are shown. In addition, there is an overall uncertainty in normalization of 5%. Uncertainties due to type of background in the fit to the missing mass spectrum are less than the statistical errors shown. All the reactions have a maximum near $t = -m_K^2$ and decrease as $t \rightarrow 0$, a structure suggestive of the presence of K exchange. If our data are integrated, assuming an e^{3t} dependence at large t, as seen in $K^+\Lambda$ and $K^+\Sigma^o$ production, we find that at 11 GeV

$$\sigma_{tot}(\Lambda) = \frac{6.7 \pm 0.4}{k^2}\ \mu b$$

$$\sigma_{tot}(\Sigma^o) = \frac{5.1 \pm 0.5}{k^2}\ \mu b$$

$$\sigma_{tot}(\Sigma^o_{1385}) + \sigma_{tot}(\Lambda_{1405}) = \frac{(3.7 \pm 1.3)}{k^2}\ \mu b$$

$$\sigma_{tot}(\Lambda^o_{1520}) = \frac{(5.4 \pm 1.4)}{k^2}\ \mu b \quad ,$$

where k is the lab photon energy in GeV. Bubble chamber results[4] in the range 2 to 5.8 GeV give

$$\sigma_{tot}(\Sigma^o_{1385}) = \frac{(1.5 \pm 0.9)}{k^2}\ \mu b$$

If this reaction scales as k^{-2} as does $K^+\Lambda$ and $K\Sigma^o$ photoproduction, this implies that about 1/3 of our step near $M_x = 1400$ is Σ^o_{1385}.

The cross sections from deuterium are given as ratios to hydrogen cross sections in Fig. 3. The errors shown are statistical only and an additional uncertainty of 5% is present in the D_2/H_2 ratio due to uncertainties in hydrogen density (1%), deuterium density (1.4%), hydrogen purity (2%) and deuterium purity (1%). The densities and corresponding temperatures measured in the targets are 0.0705 gm/cm^3 at 20.8^{o}K for hydrogen and 0.1687 gm/cm^3 at 21.1^{o}K for deuterium. The $K^+\Lambda$ production is nearly the same from D_2 as H_2, suggesting that absorption in the deuterium nucleus is not large, and it is reasonable to subtract hydrogen cross sections from deuterium cross sections to get cross sections from neutrons. From simple absorption considerations[5] the expected D_2/H_2 ratio for $K^+\Lambda$ production is

$$R_\Lambda = \frac{\sigma(\gamma d \rightarrow K^+\Lambda n)}{\sigma(\gamma p \rightarrow K^+\Lambda)} = 1 - \frac{\sigma_{total}(\gamma n) + \sigma_{total}(K^+n)}{4\pi} \langle r^{-2} \rangle$$

where $\langle r^{-2} \rangle / 4\pi$ is calculated from the deuterium wave function and represents the probability of the spectator nucleon being in the path of the incident γ or the produced K^+. For $\sigma_{total}(\gamma n) = 117\ \mu b$, $\sigma_{total}(K^+n) = 18$ mb, $\langle r^{-2} \rangle = 0.3$ $(\text{fermi})^{-2} = 0.03\ (\text{mb})^{-1}$, then $R_\Lambda = 0.957$. The average ratio found experimentally is $R_\Lambda = 1.02$ with a statistical standard deviation error of ±0.04 and a systematic uncertainty of ±0.05 and therefore consistent with $R_\Lambda = 0.957$.

In terms of isospin and helicity amplitudes the $K^+\Sigma$ cross sections can be written as

$$\sigma(\gamma n \rightarrow K^+\Sigma^-) = \sum_\lambda \left| A^\lambda_{(1/2)0} - A^\lambda_{(1/2)1} + A^\lambda_{(3/2)1} \right|^2$$

$$\sigma(\gamma p \rightarrow K^+\Sigma^o) = 1/2 \sum_\lambda \left| A^\lambda_{(1/2)0} - A^\lambda_{(1/2)1} - 2A^\lambda_{(3/2)1} \right|^2$$

where A_{I,I_γ} corresponds to exchange of isospin I, coupled to a photon with total I-spin I_γ and where λ designates the initial and the final helicities. For pure isospin-1/2 exchange ($A^\lambda_{(3/2)1} = 0$), a definite ratio at all momentum transfers must hold.

$$\frac{\frac{d\sigma}{dt}(\gamma n \to K^+\Sigma^-)}{\frac{d\sigma}{dt}(\gamma p \to K^+\Sigma^o)} = 2.0 \quad .$$

The D_2/H_2 ratio for $K^+\Sigma$ production via I-spin 1/2 exchange then is $R_\Sigma = 3$ for no absorption or $R_\Sigma = 2.87$ for simple absorption as given above.[6] The experimental average over t is $R_\Sigma = 2.37 \pm 0.11$ with a systematic error of ± 0.05. The experimental ratio R_Σ was also calculated from the raw data in another manner which makes it independent of systematic errors in the D_2 and H_2 densities and independent of the absorption correction. For each missing mass spectrum the ratio of Σ to Λ production was calculated and the corresponding statistical error using the proper correlations from the fit. This ratio is <u>independent</u> of absorption corrections if the corrections are the same for Λ and Σ final states. The D_2/H_2 ratio is then calculated as

$$R_\Sigma = \frac{\sigma(\gamma d \to K^+\Sigma\ N)/\sigma(\gamma d \to K^+\Lambda n)}{\sigma(\gamma p \to K^+\Sigma^o)/\sigma(\gamma p \to K^+\Lambda)} \quad .$$

The average experimental ratio found this way is $R_\Sigma = 2.07 \pm 0.19$ which is to be compared with an expected $R_\Sigma = 3$ for only I = 1/2 exchange. The data therefore appear to be inconsistent with only I = 1/2 exchange. An I = 3/2 amplitude of the order of 6% of the I = 1/2 amplitudes is sufficient to reproduce the experimental ratio. Such an amplitude could be due to exotic meson exchange, the exchange of two particles or S-channel effects.

SU(3) may be used to relate photoproduction of $K\Sigma_{1385}$ to $\pi\Delta_{1236}$. Assuming the photon is a U-spin singlet, SU(3) predicts that

$$\frac{d\sigma}{dt}(\gamma p \to K^+\Sigma^o_{1385}) = \frac{1}{2}\frac{d\sigma}{dt}(\gamma p \to \pi^+\Delta^o)$$

$$\frac{d\sigma}{dt}(\gamma n \to K^+\Sigma^-_{1385}) = \frac{1}{3}\frac{d\sigma}{dt}(\gamma n \to \pi^+\Delta^-) \quad .$$

In Fig. 4 we compare $K\Sigma_{1385}$ data at 11 GeV with $\pi\Delta$ data[7] at 16 GeV scaling by $(S-M^2)^2$ to remove the energy dependence in $\frac{d\sigma}{dt}$. This scaling is equivalent to a Regge trajectory of $\alpha(t) = 0$ as has been measured[8] for $\gamma p \to \pi^-\Delta^{++}$ and other forward-meson photoproduction. Using $\alpha(t) = \pm 0.2$ would change the comparison in Fig. 4 by only ± 16%. We find $K\Sigma_{1385}$ cross sections much too small relative to the $\pi\Delta$ cross sections to satisfy SU(3).

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2. B. C. Cook, Nuclear Instruments and Methods 24, 256 (1963).
3. D. H. White, R. M. Schectman, and B. M. Chasan, Phys. Rev. 120, 614 (1960).
4. Aachen-Berlin-Bonn-Hamburg-Heidelberg-Munchen Collaboration, Nuovo Cimento 49A, 505 (1967) and DESY Report 69/19; Cambridge Bubble Chamber Group, Phys. Rev. 156, 1426 (1967).
5. Arnon Dar and Avraham Gal, Phys. Rev. Letters 21, 444 (1968).
6. If vector-meson dominance is invoked, one replaces $\sigma_{\text{total}}(\gamma n)$ with $\sigma_{\text{total}}(\rho^0 n) \approx 27$ mb. See Arnon Dar and Avraham Gal, Phys. Rev. D1, 2714 (1970). This changes the expected D_2/H_2 ratios due to absorption to $R_\Lambda = 0.89$ and $R_\Sigma = 2.67$ differing from experiment by 0.13 ± 0.04 (statistics) ± 0.05 (systematics) and $0.30 \pm 0.11 \pm 0.05$, respectively. We note however that vector-meson dominance has not been entirely successful in complex nuclei; the indication being that photons interact in nuclear matter with a cross section intermediate between the free-photon cross section $\sigma_{\text{total}}(\gamma n)$ and $\sigma_{\text{total}}(\rho n)$. See Boyarski et al., Phys. Rev. Letters 23, 1343 (1969), D. O. Caldwell et al., Phys. Rev. Letters 23, 1256 (1969), and H. Meyer et al., Proceedings of the Conference on Photon and Electron Interactions, Daresbury, England, 15-19 September 1969.
7. A. M. Boyarski et al., Photoproduction of $\pi^\pm\Delta(1236)$ Hydrogen and Deuterium at 16 GeV, Report No. SLAC-PUB-744 (1970).
8. A. M. Boyarski et al., Phys. Rev. Letters 22, 148 (1969).

TABLE I

The cross section per nucleus $d\sigma/dt$ in units of microbarns per GeV^2 is tabulated for steps measured from hydrogen and deuterium. The laboratory angle is given in degrees and momentum transfer squared (t) in units of GeV^2.

$\gamma p \rightarrow K^+$

θ_{LAB}	-t	Λ^o	Σ^o	$\Lambda^o_{1405} + \Sigma^o_{1385}$	Λ_{1520}
0.70	0.025	0.070 ± 0.004	0.042 ± 0.005	0.022 ± 0.019	0.044 ± 0.021
1.03	0.045	0.081 ± 0.003	0.042 ± 0.004	0.040 ± 0.010	0.036 ± 0.011
2.15	0.17	0.090 ± 0.005	0.072 ± 0.005	0.062 ± 0.009	0.071 ± 0.012
2.96	0.32	0.075 ± 0.005	0.065 ± 0.006	0.047 ± 0.015	0.065 ± 0.016
3.57	0.46	0.061 ± 0.003	0.044 ± 0.003	0.025 ± 0.009	0.046 ± 0.010
4.35	0.67	0.030 ± 0.002	0.025 ± 0.003	0.019 ± 0.008	0.032 ± 0.009

$\gamma d \rightarrow K^+$

θ_{LAB}	-t	Λ^o	$\Sigma^{\underline{o}}$	$\Lambda_{1405} + \Sigma^{\underline{o}}$
0.70	0.025	0.072 ± 0.006	0.094 ± 0.007	0.064 ± 0.029
1.03	0.045	0.078 ± 0.004	0.111 ± 0.004	0.059 ± 0.012
2.15	0.17	0.098 ± 0.006	0.167 ± 0.007	0.059 ± 0.029
2.96	0.32	0.087 ± 0.009	0.141 ± 0.009	0.047 ± 0.034
3.57	0.46	0.066 ± 0.006	0.107 ± 0.007	0.019 ± 0.032

LIST OF FIGURES

1. One of the missing mass spectra obtained from hydrogen. The upper graph (a) is a derivative of the actual measured yields (b). The smooth curves represent fits to the measured yields consisting of the sum of phase space and four steps corresponding to production of Λ, Σ, $\Sigma_{1385} + \Lambda_{1405}$, and Λ_{1520}.
2. The γp cross sections from hydrogen vs momentum transfer squared. The Σ_{1385} and Λ_{1405} are not resolved and consequently the sum of their cross sections is given.
3. The ratio of production from deuterium to production from hydrogen.
4. SU(3) comparison of $\pi\Delta_{1236}$ and $K\Sigma_{1385}$ photoproduction assuming the photon is a U-spin singlet. Since our resolution cannot separate Σ_{1385} and Λ_{1405} we have plotted the sum of these cross sections in (a) which by SU(3) must be $\geq$ one-half the $\pi\Delta$ cross section.

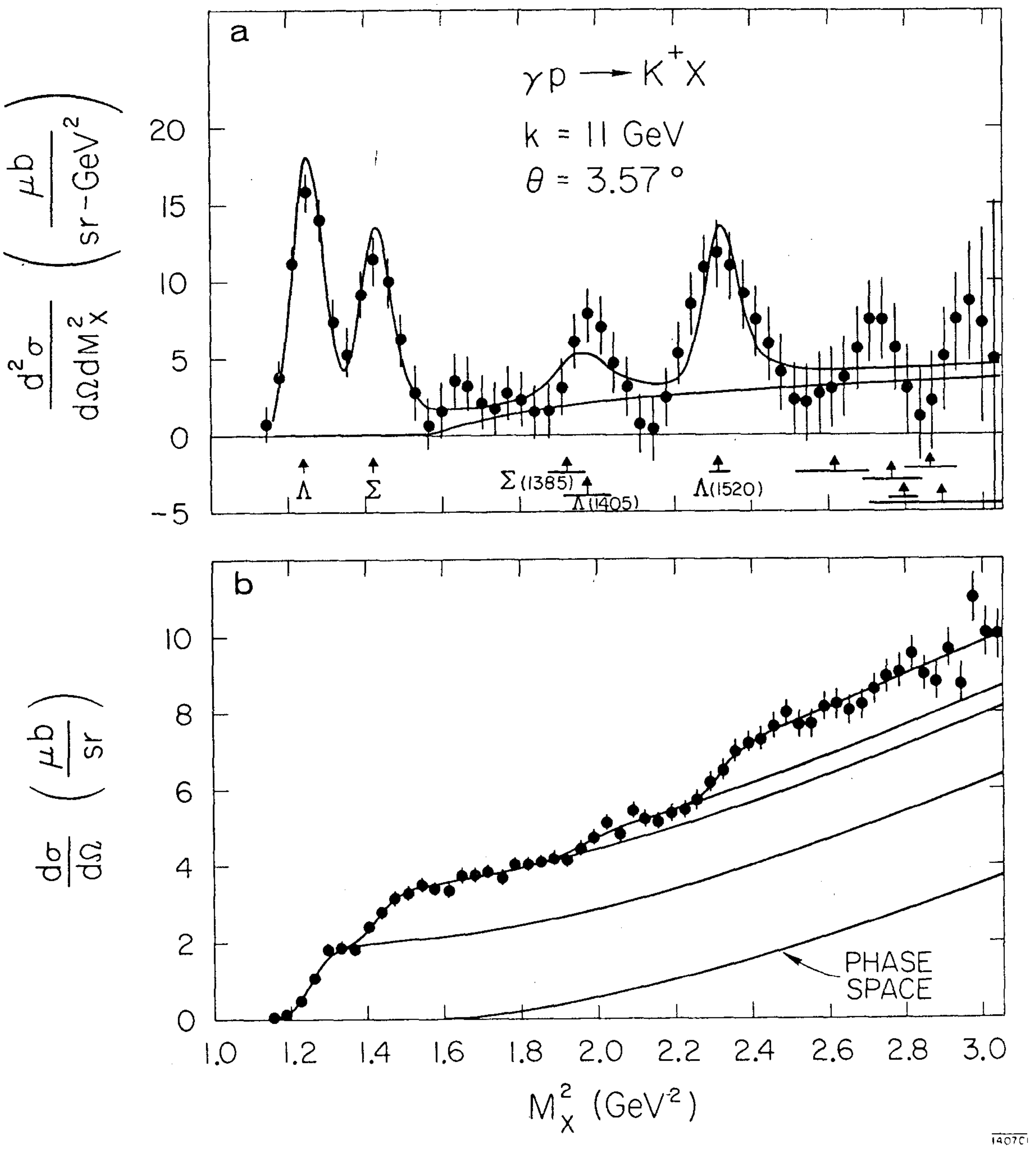
a
γp → K+X
k = 11 GeV
θ = 3.57°
d²σ/dΩdM²X (μb/sr-GeV²)
20
15
10
5
0
-5
Λ
Σ
Σ(1385)
Λ(1405)
Λ(1520)
b
dσ/dΩ (μb/sr)
10
8
6
4
2
0
PHASE SPACE
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
M²X (GeV²)
1407C1

Fig. 1

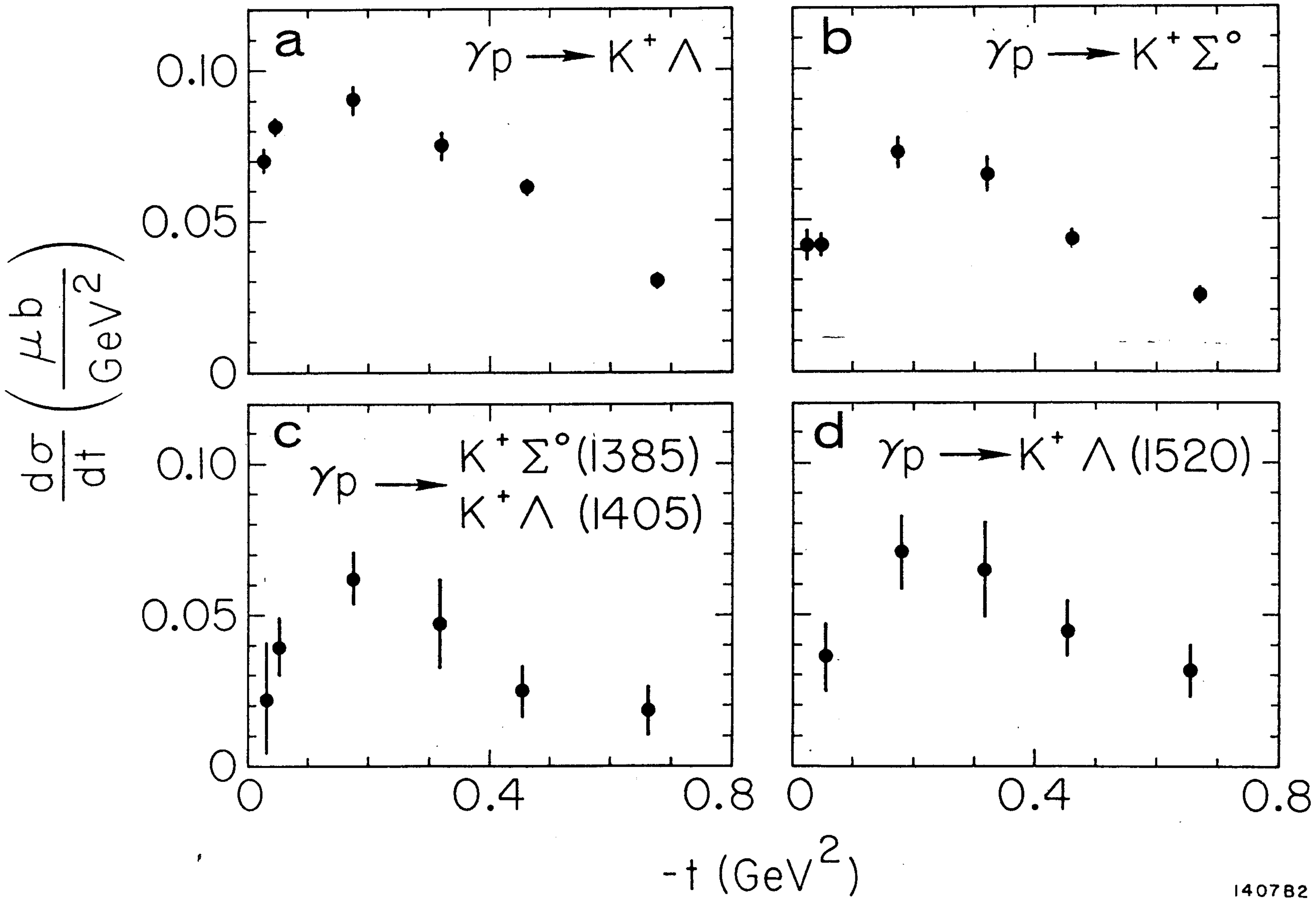
a
$\gamma p \to K^+ \Lambda$
b
$\gamma p \to K^+ \Sigma^\circ$
c
$\gamma p \to K^+ \Sigma^\circ(1385)$
$K^+ \Lambda\ (1405)$
d
$\gamma p \to K^+ \Lambda\ (1520)$
0.10
0.05
0
0
0.4
0.8
$\frac{d\sigma}{dt} \left(\frac{\mu b}{GeV^2}\right)$
$-t\ (GeV^2)$
140782

Fig. 2

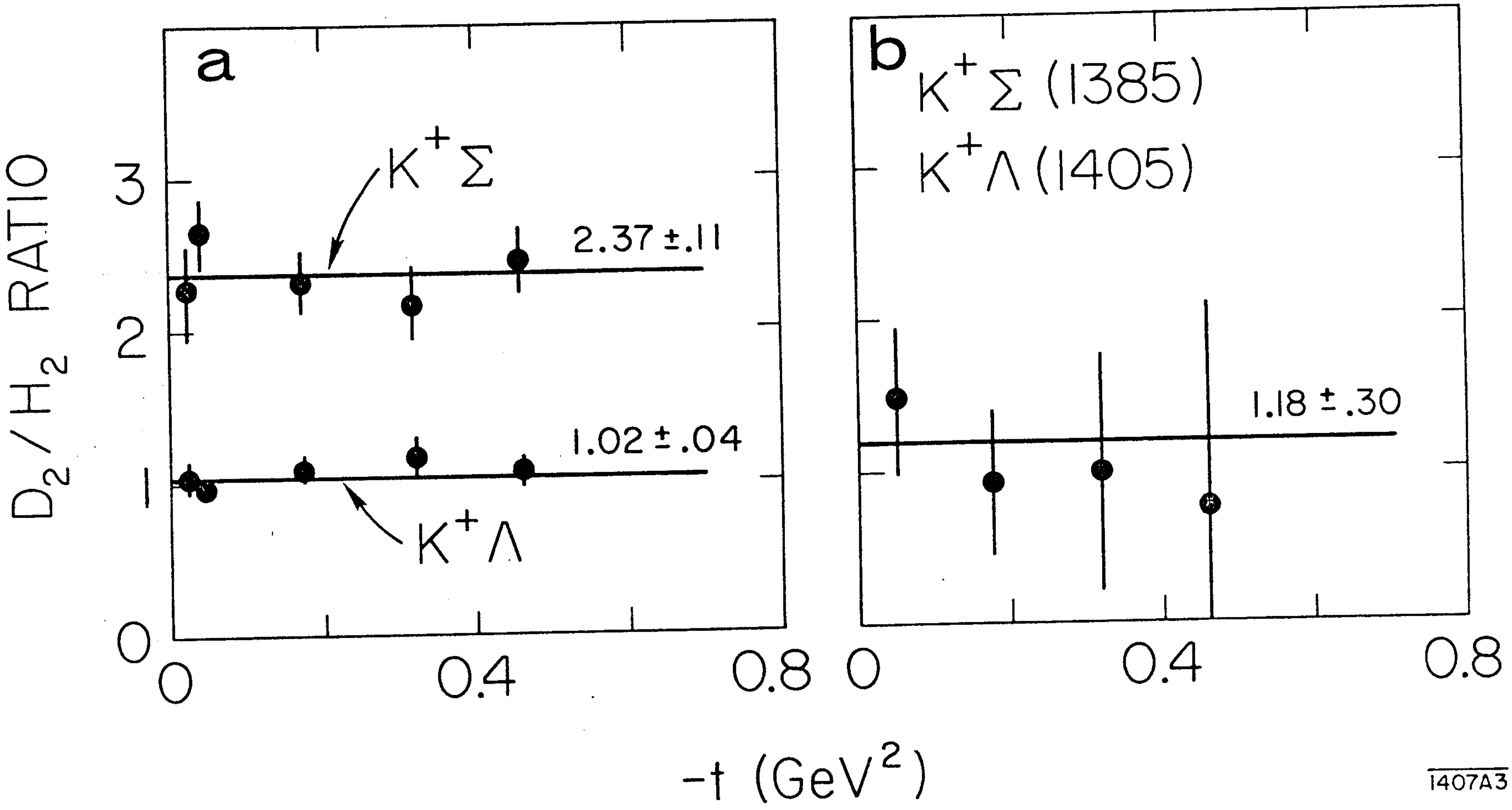
a
b
$K^+\Sigma$
$K^+\Lambda$
2.37 ± .11
1.02 ± .04
$K^+\Sigma(1385)$
$K^+\Lambda(1405)$
1.18 ± .30
D_2/H_2 RATIO
0
1
2
3
0
0.4
0.8
0
0.4
0.8
$-t$ (GeV^2)
1407A3

Fig. 3

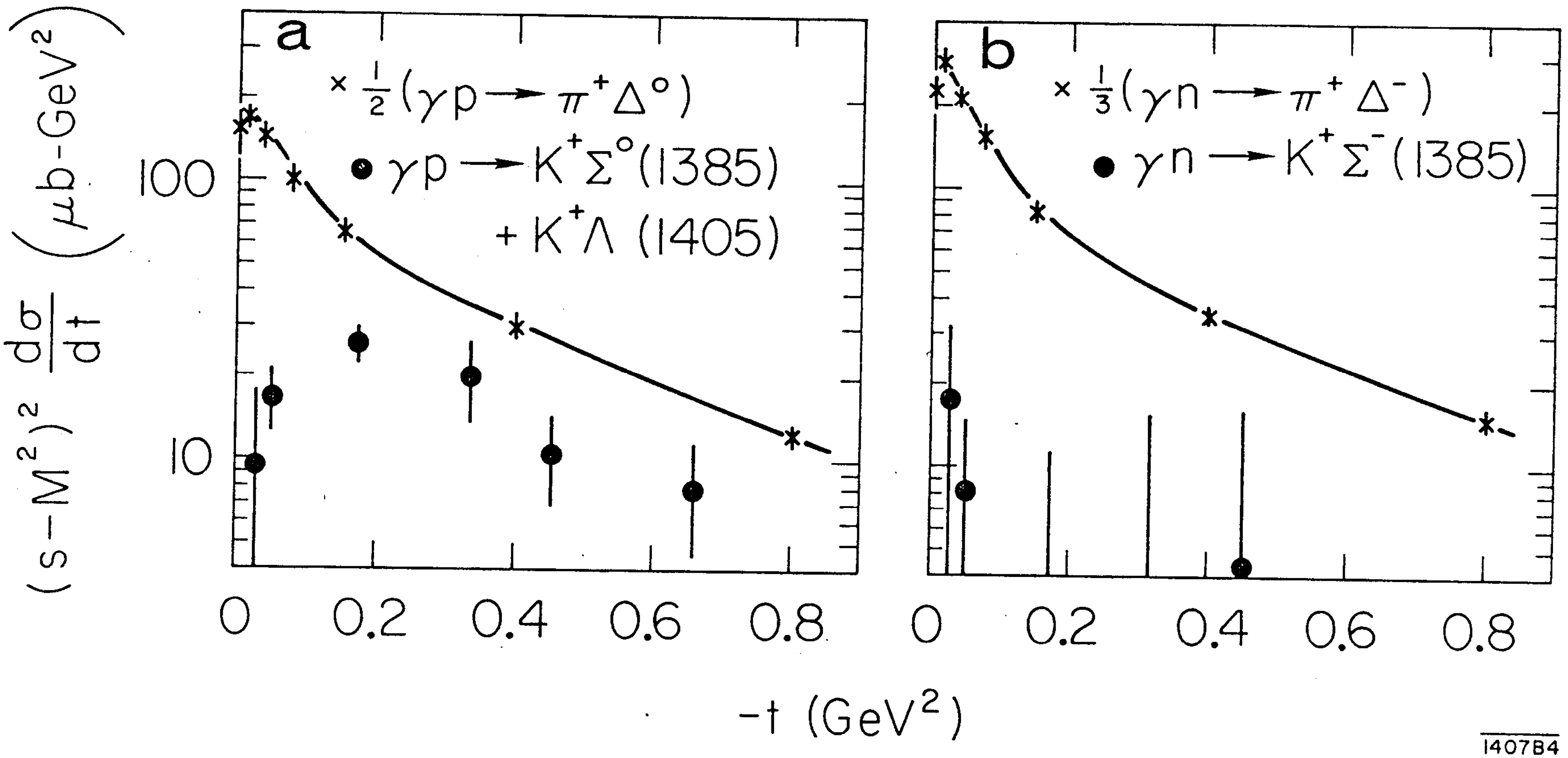
a
× $\frac{1}{2}(\gamma p \rightarrow \pi^+ \Delta^0)$
● $\gamma p \rightarrow K^+ \Sigma^0(1385)$
$+ K^+ \Lambda(1405)$
b
× $\frac{1}{3}(\gamma n \rightarrow \pi^+ \Delta^-)$
● $\gamma n \rightarrow K^+ \Sigma^-(1385)$
$(s-M^2)^2 \frac{d\sigma}{dt}$ $(\mu b\text{-GeV}^2)$
100
10
0
0.2
0.4
0.6
0.8
0
0.2
0.4
0.6
0.8
$-t$ (GeV^2)
1407B4

Fig. 4