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# SINGLE $\pi^{\pm}$ AND $K^+$ PHOTOPRODUCTION FROM COMPLEX NUCLEI AT 8 AND 16 GeV*

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## ABSTRACT

The reactions $\gamma A \rightarrow \pi^{\pm} A^*$ have been studied at four-momentum transfers $-t \leq 0.5$ GeV$^2$ for seven elements ranging from hydrogen to lead. Exclusion-principle suppression is clearly visible at small-momentum transfer. Neither the A dependence nor the energy dependence of the cross sections agrees with the predictions of the vector dominance model. The ratio of $\pi^-/\pi^+$ production requires equal spatial distributions for the protons and neutrons in nuclei. Some $K^+$ data are also presented.

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Several studies have been made of diffraction-like processes in complex nuclei at high energies, for example, proton elastic and quasi-elastic scattering[1] and $\rho^0$ photoproduction.[2] Results are presented here on the processes

$$\gamma A \rightarrow \begin{Bmatrix} \pi^+ \\ \pi^- \\ K^+ \end{Bmatrix} + \text{nuclear stuff}$$

at laboratory photon energies of 8 and 16 GeV and four-momentum transfers $-t \lesssim 0.5$ GeV$^2$. In contrast to the diffraction processes, the individual nucleon amplitudes are expected to contribute incoherently to these charge exchange reactions and the information obtained from their study is largely complementary to the previous work. These processes are of particular current interest since recent theoretical work has related the A dependence of photoproduction from nuclei to the hypothesis of vector meson dominance.

Data were obtained from targets of $CH_2$, Be, C, Al, Cu, Ag, and Pb. Charged mesons were detected and momentum-analyzed with the SLAC 20 GeV/c spectrometer system and, as in previous work,[3] no attempt was made to observe the recoiling nuclear matter. By working close to the bremsstrahlung end-point energy, the single-meson production events could be separated from multimeson processes by energy conservation. The experimental resolution is much too coarse to detect the excitation of individual nuclear levels, and all nuclear final states with excitations of less than about 100 MeV are accepted.

The cross sections were found by fitting the momentum distribution of the mesons near the bremsstrahlung end-point. The form used was obtained by folding the experimental resolution and the effects of the momentum distribution of the nucleons in the target nucleus, with the bremsstrahlung distribution plus a linear term starting at the multimeson production threshold (for $K^+$ data, two bremsstrahlung steps were used, corresponding to $\Lambda$ and $\Sigma$ production). The effective resolution was dominated at all but the smallest momentum transfers by the momentum distribution of the target nucleons. The fitting function was allowed to slide along the energy axis, the best fit position being related to Q, the average energy given to the nuclear matter.

For the fit the nucleus was assumed to be a condensed Fermi gas with a maximum momentum of 260 MeV/c. The total $\chi^2$ for the 62 fits was 971 for 931 degrees of freedom. These fits gave Q $\approx$16 MeV, with no obvious dependence on A or momentum transfer. Run-to-run fluctuations in Q of 5 or 10 MeV (due to beam instabilities) preclude a detailed analysis.

Cutoffs of 220 or 300 MeV/c for the internal nuclear momentum also gave quite acceptable fits, although the $\chi^2$'s did increase slightly. A large variation of Q with momentum transfer was shown by these fits, however, and the cutoff momentum appears to be limited to the region between about 220 and 300 MeV/c if Q is to remain positive. Varying the cutoff momentum by $\pm$40 MeV/c changed the fitted cross sections in a systematic way by amounts ranging from $\pm$16% at the largest momentum transfer to $\pm$1% at the smallest. However, the A dependence of the cross sections at a given momentum transfer is very nearly independent of the cutoff, the worst case giving $\pm$3% in the Pb-to-C ratio. For some of the points a nucleon momentum distribution with a smooth variation at the upper end was tried. This gave a negligible change in the fitted cross sections.

The $CH_2$-C data gave us a check on experimental resolution and the step position from hydrogen; it also allowed a comparison of the normalization of this experiment with previous experiments done with liquid hydrogen targets. The $CH_2$-C data gave cross sections about 4% higher than the previously published values,[3] well within the estimated 7% systematic errors.

Figure 1 shows the experimental results for $\pi^+$ production; $Z_{eff}\left(\frac{d\sigma}{dt}\text{ from a nucleus}\Big/\frac{d\sigma}{dt}\text{ from hydrogen}\right)$ is plotted vs $\ell n Z$, (the measured cross sections are given in the table). The 8 and 16 GeV results are consistent with no energy dependence of $Z_{eff}$($\chi^2$ = 12/13 degree of freedom). The effect of nucleon correlations (exclusion principle) can be clearly seen. For example, $Z_{eff}(Cu)$ decreases from about 11 at $-t = 0.45\ (GeV/c)^2$ to about 4.5 at $-t = 0.01\ (GeV/c)^2$. A classical calculation with the condensed Fermi gas model (cutoff = 260 MeV/c) does not agree well with the data; at 0.01 $(GeV/c)^2$ it predicts a factor of 1.5 more suppression than is observed. This may be the result of rescattering and/or collective excitations of the nucleus.

The vector dominance model predicts that $\gamma$-ray interactions will have the same A dependence as those of strongly interacting particles.[4] Gottfried and Yennie, in particular, have developed the theory for the process under study here. In this theory the amplitude for the $\gamma$-ray to directly produce a $\pi^+$ at some point in the nucleus must be added to the amplitude corresponding to coherent production of real vector mesons which then propagate through the nucleus and interact at the same point as the direct $\gamma$-ray to produce a $\pi^+$. A destructive interference occurs between the two amplitudes, resulting at high energies in the simple vector dominance result $\sigma(\gamma A) \propto \sigma(VA)$. For lead, for example, this shadowing effect is large, and $Z_{eff}$ is reduced from 25 down to 6 at high energies.

The cross sections predicted by the Gottfried-Yennie model were calculated assuming a Woods-Saxon nuclear density distribution,

$$\rho(r) = \frac{\rho_0}{1 + e^{(r-c)/a}} \quad ,$$

with $c = 1.14\ A^{1/3}$ fermi, $a = 0.545$ fermi, and total cross sections on single nucleons of $\sigma_\rho = \sigma_\omega = 32$ mb, $\sigma_\pi = 26$ mb. The real parts of the $\rho$ and $\omega$ forward elastic scattering amplitudes were taken as zero. Since the Gottfried-Yennie model does not include nucleon correlation terms, we felt that the Z dependence rather than the absolute value of these cross sections was the most reasonable test of this model. Accordingly, the curves in Fig. 1 are the predictions of the model normalized to the carbon data at each momentum transfer. The normalization factors (experiment/theory) are 1.55, 1.25, 0.92, 0.71 at $-t = 0.45$, 0.16, 0.04, 0.01, respectively. The experimental errors on $Z_{eff}$ (carbon), and thus on the normalization, are ~5% (many of the possible systematic errors drop out when taking the carbon - to - hydrogen ratio).

At 16 GeV where the shadowing effects should be largest, the A dependence of the data clearly disagrees with the model. Further, the large energy dependence predicted by the model is not observed. At $-t = 0.45$ GeV$^2$, where the correlation effects should be negligible, the normalization factor of 1.55 represents an additional discrepancy between the data and model. In order to get some feel for the size of the discrepancy, we have parameterized the model by a constant w which multiplies the amplitude of the vector meson term ($w \equiv 1$ if vector dominance is saturated by the $\rho$ and $\omega$ and $w \equiv 0$ if the vector meson graph makes no contribution). The Z dependence of the Al through Pb data gives $w = 0.31 \pm 0.08$. The beryllium and carbon data were not used since the simple Woods-Saxon distribution is probably not a good representation of these nuclei.[5] Significant data in this range of A exist only at 0.16 (GeV/c)$^2$ at 8 GeV and 0.04, 0.16 and 0.45 (GeV/c)$^2$ at 16 GeV. All four distributions gave results in good agreement with the average value, implying that the correlation effects are to a good approximation independent of A.

Changing the radius parameter c by $\pm 0.06\, A^{1/3}$ fermi changes w by $\pm 0.08$; $\Delta a = \pm 0.1$ fermi gives $\Delta w = \pm 0.02$; $\Delta\sigma_\rho = \pm 6$ mb gives $\Delta w = \pm 0.02$; a ratio of real to imaginary part of $\pm 0.3$ in the $\rho$ and $\omega$ forward amplitudes gives $\Delta w = \pm 0.01$. Combining all these effects leads to $w = 0.31 \pm 0.12$.

There now exist several experiments on photon reactions in complex nuclei, none of them giving good agreement with the vector dominance model. The large energy dependence predicted by this model is not seen in the preliminary results on $\gamma A$ total cross sections,[6] in incoherent $\rho^0$ photoproduction,[7] or in this experiment. All three experiments are consistent with a shadowing amplitude considerably smaller than that predicted by the VDM. Schmidt and Yennie[8] have recently attempted to explain these discrepancies in terms of a mass dependence in the vector meson amplitudes. Their calculation is a qualitative one which goes in the right direction, but no quantitative comparison with experiment is attempted. In any event it seems clear that the d notions of simple vector dominance do not work.

Cross sections for $\pi^-$ photoproduction were measured at 16 GeV, $-t = 0.16$ GeV$^2$; the results are shown in Fig. 2a. The $\pi^-/\pi^+$ ratios from complex nuclei are in good agreement with the ratio previously obtained from deuterium.[9] The weighted average of all the points is shown in the figure; $\chi^2$ for the ratio being independent of A is 7.5 for 6 degrees of freedom.

Single pions come predominately from the nuclear surface; a pion produced deep inside the nucleus has a much smaller probability of escaping without inelastic collisions. This makes the $\pi^-/\pi^+$ ratio quite sensitive to any difference in the neutron and proton spatial distributions near the surface of the nucleus.[10] The differences in distributions allowed by our data were calculated for independent Woods-Saxon distributions for the protons and neutrons. Assuming equal skin thicknesses ($a_n = a_p$), the difference in radii ($c_n - c_p$) for Ag and Pb are, respectively, $-0.25 \pm 0.4$, and $-0.7 \pm 0.4$ fermi. Assuming equal radii, the differences in skin thickness ($a_n - a_p$) are, respectively, $-0.15 \pm 0.2$, and $-0.3 \pm 0.2$ fermi. The Pb result is consistent with the calculation of Bethe and Siemens[11] which gives a smaller neutron radius than proton radius, but is not consistent with one of the conventional interpretations of K mesic X-ray data in terms of neutron radius or skin thickness considerably larger than that of the proton distribution.[12] The $\pi^-/\pi^+$ ratio may also give information on proton-neutron correlations.[13]

The A dependence of $K^+$ photoproduction was measured at $-t = 0.043$ GeV$^2$ and $k = 16$ GeV. Because of the small separation between the $\Lambda$ and $\Sigma$ steps and the smearing effects of the nucleon momentum in the nucleus, the $\Lambda$ and $\Sigma$ cross sections obtained from the fitting procedure are strongly correlated. The $\Lambda + \Sigma$ cross sections can be determined much more reliably since the background from multiple production processes is farther away than the separation between $\Lambda$ and $\Sigma$

thresholds. The fitted $\Lambda$ and $\Lambda + \Sigma$ cross sections are given in the table; the errors on the $\Lambda$ given in the table do not include $\Lambda - \Sigma$ correlations.

Direct comparison of the A dependence of the $K^+$ and $\pi^+$ data is not possible since $K^+$ can be produced from neutrons (in association with a $\Sigma^-$) as well as from the proton ($\Lambda + \Sigma^o$). In an auxiliary experiment we determined that $\Sigma^-/(\Lambda + \Sigma^o) = 0.53 \pm 0.05$ from single nucleons. Then,

$$\frac{d\sigma}{dt}[\gamma A \rightarrow K^+(\Lambda + \Sigma^o)] = \frac{1}{1 + 0.53\frac{N}{Z}} \frac{d\sigma}{dt}[\gamma A \rightarrow K^+(\Lambda + \Sigma^o + \Sigma^-)].$$

The ratio of this quantity to $\gamma A \rightarrow \pi^+ A^*$ is shown in Fig. 2b. $Z^K_{eff}/Z^\pi_{eff}$ increases with A. This increase would be expected in any model, since the cross section for $K^+$ on nucleons is smaller than that for $\pi^+$ (17 mb vs 26 mb). The curve in Fig. 2b is the prediction of the VDM theory with w = 0.3 (normalized to the Be through Pb data). The difference between the hydrogen point and the curve in Fig. 2b is presumably due to the exclusion-principle suppression of $\pi^+$ production in the complex nuclei. The hydrogen point is low by a factor 0.57 ± 0.09 which is in good agreement with an estimate of the suppression obtained by comparing $Z_{eff}$ for $\pi^+$ production at $-t = 0.45$ and 0.04, the ratio (averaged over nuclei) being 0.53 ± 0.06.

Since the vector dominance model has failed to fit the $\pi^+$ data, we have also used a less detailed model for the K data in which the incoming $\gamma$-ray and out-going K meson are assumed to have attenuation cross sections of $\sigma_\gamma$ and $\sigma_K$ in nuclear matter. $A_{eff}$ is defined by the expression

$$A_{eff}/A = \sigma(A)/\left[N\sigma_N + Z\sigma_p\right],$$

where N and Z are the number of neutrons and protons in the nucleus A. $A_{eff}$ is given in terms of $\sigma_\gamma$ and $\sigma_K$ in the impact parameter model as

$$A_{eff} = \iint d^3x\rho \exp - \left\{\sigma_\gamma \int_{-\infty}^{Z} \rho dZ + \sigma_K \int_{Z}^{\infty} \rho dZ\right\},$$

where $\rho$ is the Woods-Saxon density distribution used previously.

Taking $\sigma_K = 17$ mb as found in K-nucleon total cross section measurements gives $\sigma_\gamma = 4.1 \pm 0.9$ mb. Taking $\sigma_\gamma = 0$ gives $\sigma_K = 25.0 \pm 1$ mb. The choice of the "correct" K total cross section in nuclear matter is not at all obvious, but using the free nucleon value, we conclude that the photon does have an "anomalous" cross section in nuclear matter, but that the magnitude of this cross section is not correctly given by the vector dominance model.

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Table. Single Charged Meson Photoproduction Cross Sections from Co

(All cross sections are $\frac{d\sigma}{dt}$ in $\mu b/GeV^2$; errors are statist

| Meson | $\pi^+$ | $\pi^+$ | $\pi^+$ | $\pi^+$ | $\pi^+$ |
|---|---|---|---|---|---|
| k (GeV) | 8 | 8 | 8 | 8 | 8 |
| $-t\,(GeV^2)$ | ~0.003 | 0.010 | 0.039 | 0.169 | 0.45 |
| $H(CH_2-C)$ | 1.06±0.11 | 0.79±0.03 | 0.62±0.02 | 0.50±0.02 | 0.265± |
| Be | --- | --- | --- | 1.39±0.04 | --- |
| C | 1.87±0.16 | 1.48±0.05 | 1.54±0.03 | 1.63±0.03 | 1.05 ± |
| Al | --- | --- | --- | 2.50±0.08 | --- |
| Cu | --- | 3.60±0.29 | 3.76±0.19 | 4.28±0.16 | 2.62 ± |
| Ag | --- | --- | --- | 5.53±0.27 | --- |
| Pb | --- | --- | --- | 6.66±0.62 | 5.59 ± |

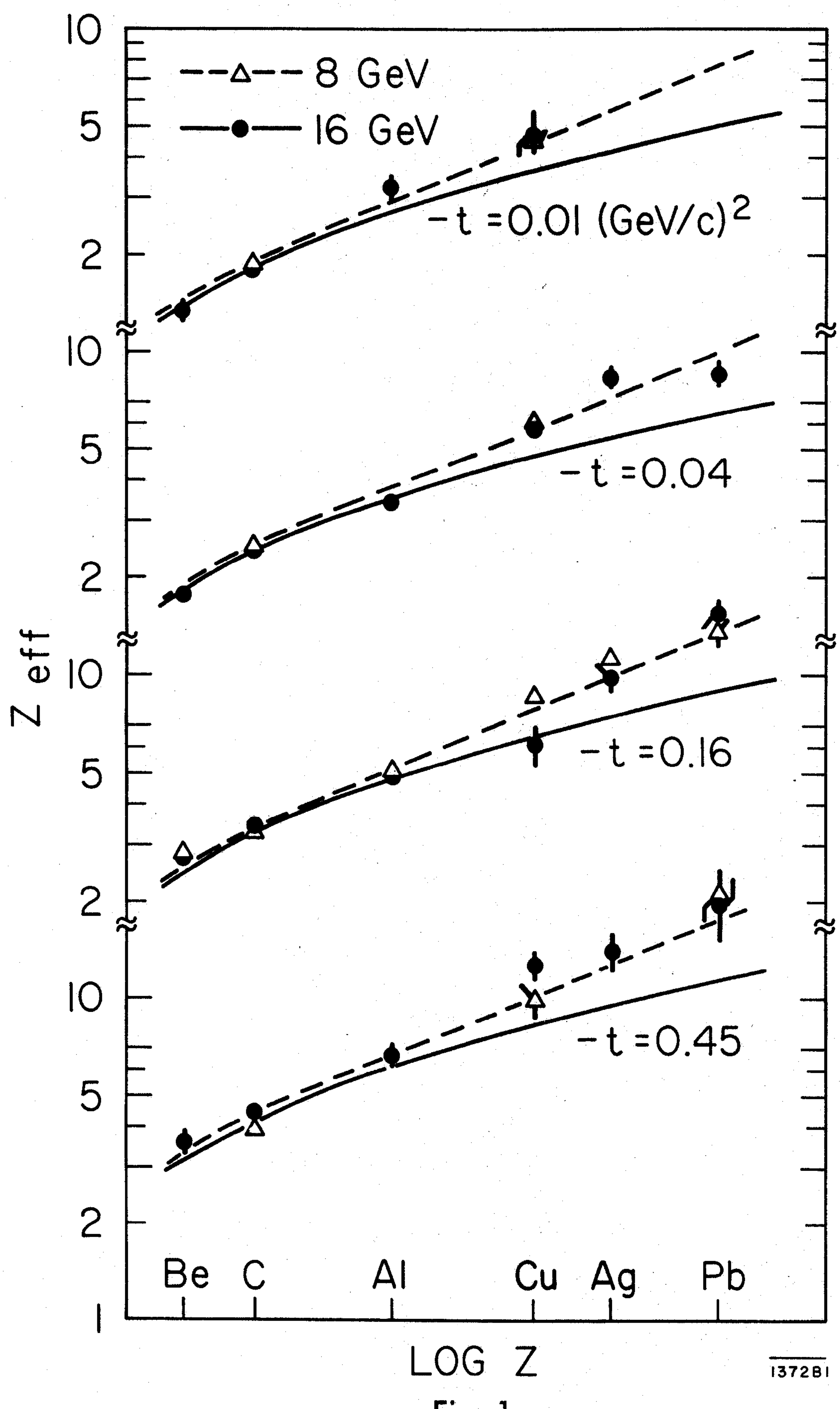
| Meson | $K^+(\Lambda+\Sigma)$ | $\pi^+$ | $\pi^+$ | $\pi^+$ | $\pi^+$ |
|---|---|---|---|---|---|
| k (GeV) | 16 | 16 | 16 | 16 | 16 |
| $-t\,(GeV^2)$ | 0.043 | ~0.010 | 0.040 | 0.153 | 0.44 |
| $H(CH_2-C)$ | 0.056±0.007 | 0.171±0.009 | 0.144±0.005 | 0.114±0.007 | 0.066± |
| Be | 0.31±0.01 | 0.230±0.015 | 0.258±0.007 | 0.308±0.015 | 0.239± |
| C | 0.38±0.01 | 0.302±0.013 | 0.346±0.007 | 0.391±0.007 | 0.298± |
| Al | 0.62±0.03 | 0.554±0.038 | 0.492±0.014 | 0.555±0.021 | 0.44 ± |
| Cu | 1.22±0.07 | 0.81 ±0.12 | 0.83 ±0.04 | 0.70 ±0.11 | 0.85 ± |
| Ag | 1.64±0.12 | --- | 1.19 ±0.07 | 1.12 ±0.11 | 0.92 ± |
| Pb | 2.8 ±0.2 | --- | 1.22 ±0.11 | 1.75 ±0.20 | 1.29 ± |

## FIGURE CAPTIONS

1. The Z dependence of $Z_{eff} = \frac{d\sigma}{dt}(\gamma A \rightarrow \pi^+ A^*) / \frac{d\sigma}{dt}(\gamma p \rightarrow \pi^+ n)$ for four different momentum transfers. The errors are statistical only. The curves were calculated using the Gottfried-Yennie prescription (Ref. 4) and have been normalized to the carbon data at each momentum transfer.

2. (a) The A dependence of the ratio $\frac{d\sigma}{dt}(\gamma A \rightarrow \pi^- A^*)/N / \frac{d\sigma}{dt}(\gamma A \rightarrow \pi^+ A^*)/Z$, where N and Z are the numbers of neutrons and protons in the nuclei. Errors are statistical only.

   (b) The A dependence of the ratio $\frac{d\sigma}{dt}(\gamma A \rightarrow K^+(\Lambda + \Sigma)$ + nuclear stuff$) / \frac{d\sigma}{dt}(\gamma A \rightarrow \pi^+ n)$, corrected for the variation of Z/N with A (see text). The curve shows the slight increase with A expected due to the difference between $\sigma(K\mathcal{N}) = 17$ mb and $\sigma(\pi\mathcal{N}) = 26$ mb.



8 GeV
16 GeV
−t =0.01 (GeV/c)$^2$
−t =0.04
−t =0.16
−t =0.45
Z eff
Be
C
Al
Cu
Ag
Pb
LOG Z
1372B1


Fig. 1

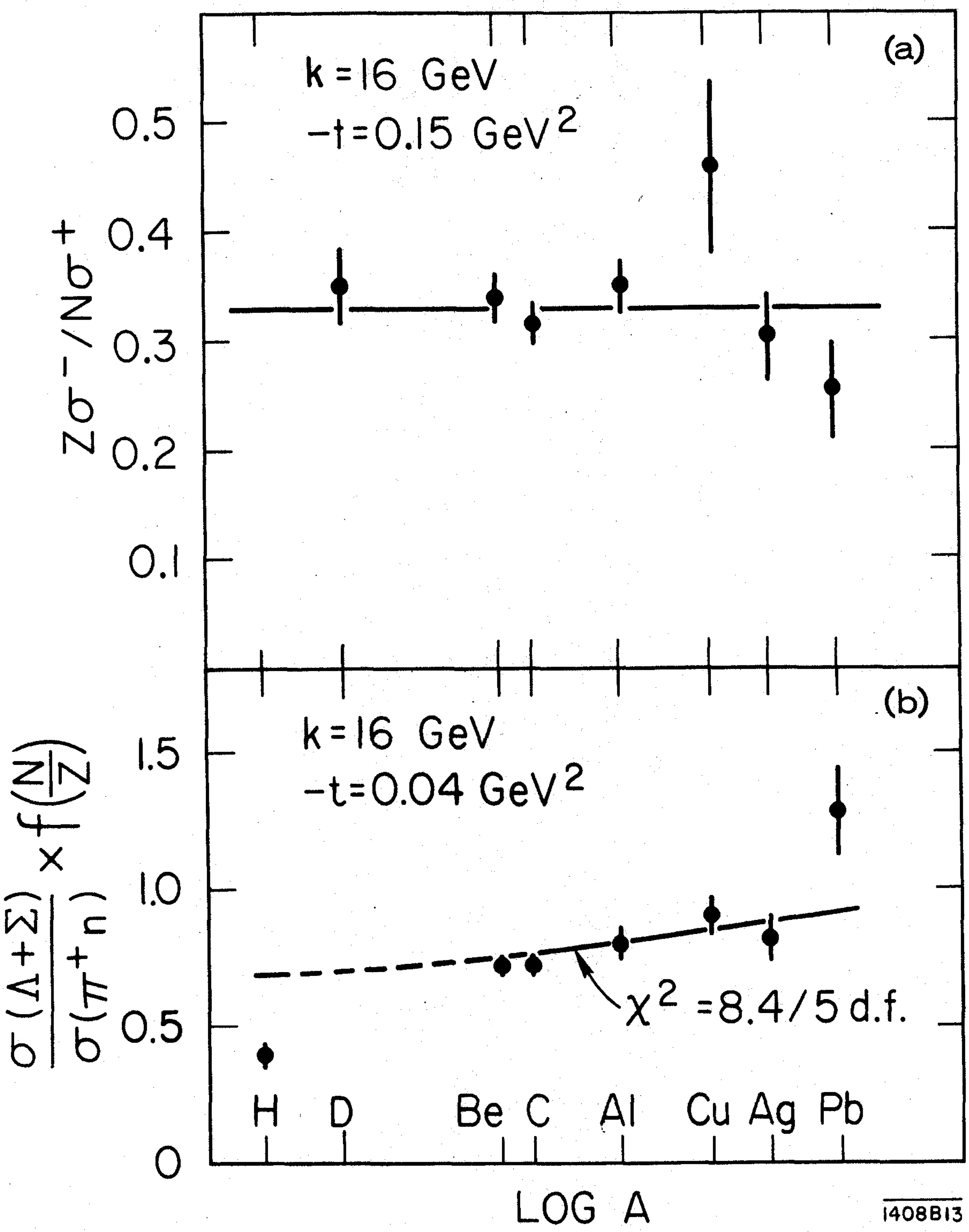

(a)
k = 16 GeV
−t = 0.15 GeV²
$Z\sigma^- / N\sigma^+$
0.5
0.4
0.3
0.2
0.1
(b)
k = 16 GeV
−t = 0.04 GeV²
$\frac{\sigma(\Lambda+\Sigma)}{\sigma(\pi^+ n)} \times f\left(\frac{N}{Z}\right)$
1.5
1.0
0.5
0
$\chi^2$ = 8.4/5 d.f.
H
D
Be
C
Al
Cu
Ag
Pb
LOG A
1408B13

Fig. 2