

SINGLE- π^\pm AND $-K^+$ PHOTOPRODUCTION FROM COMPLEX NUCLEI AT 8 AND 16 GeV*

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The reactions $\gamma A \rightarrow \pi^\pm A^*$ have been studied at four-momentum transfers $-t \leq 0.5 \text{ GeV}^2$ 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 π^-/π^+ production requires equal spatial distributions for the protons and neutrons in nuclei. Some K^+ data are also presented.

Several studies have been made of diffraction-like processes in complex nuclei at high energies, for example, proton elastic and quasielastic scattering¹ and ρ^0 photoproduction.² Results are presented here on the processes

$$\gamma A \rightarrow (\pi^\pm \text{ or } K^+) + \text{nuclear stuff}$$

at laboratory photon energies of 8 and 16 GeV and four-momentum transfers $-t \leq 0.5 \text{ GeV}^2$. 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 Stanford Linear Accelerator Center 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 Λ and Σ 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 χ^2 for the 62 fits was 971 for 931 degrees of freedom. These fits gave $Q \approx 16 \text{ MeV}$, 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 χ^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 $\pm 40 \text{ MeV/c}$ 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 π^+ production; $Z_{\text{eff}}(d\sigma/dt \text{ from a nucleus})/(d\sigma/dt \text{ from hydrogen})$ is plotted versus $\ln Z$ (the

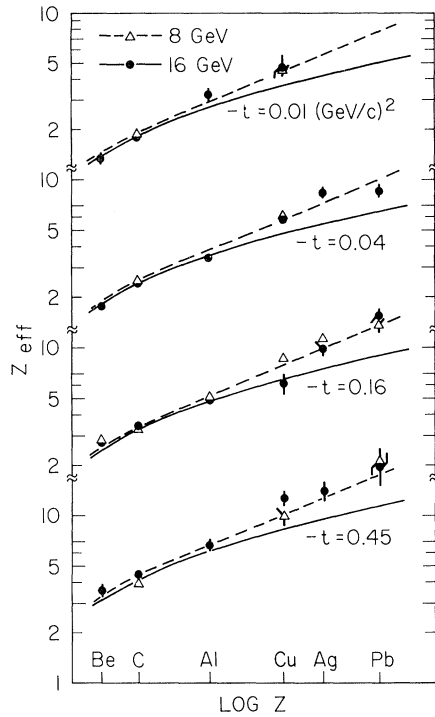


FIG. 1. The Z dependence of

$$Z_{\text{eff}} = \frac{d\sigma(\gamma A \rightarrow \pi^+ A^*)/dt}{d\sigma(\gamma p \pi^+ n)/dt}$$

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.

measured cross sections are given in Table I). The 8- and 16-GeV results are consistent with no energy dependence of Z_{eff} ($\chi^2 = 12/13$ degrees of freedom). The effect of nucleon correlations (exclusion principle) can be clearly seen. For example, $Z_{\text{eff}}(\text{Cu})$ 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 (VDM) predicts that γ -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 γ ray to produce directly a π^+ 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 γ ray to produce a π^+ . 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,

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

with $c = 1.14A^{1/3}$ F, $a = 0.545$ F, and total cross sections on single nucleons of $\sigma_\rho = \sigma_\omega = 32$ mb, $\sigma_\pi = 26$ mb. The real parts of the ρ and ω 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, and 0.71 at $-t = 0.45$, 0.16, 0.04, and 0.01, respectively. The experimental errors on $Z_{\text{eff}}(\text{carbon})$, and thus on the normalization, are $\sim 5\%$ (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 parametrized the model by a constant w which multiplies the amplitude of the vector-meson term ($w = 1$ if vector dominance is saturated by the ρ and ω and $w = 0$ if the vector-meson graph makes no contribution). The Z dependence of the data for Al through Pb 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 ef-

Table I. Single-charged-meson photoproduction cross sections from complex nuclei. (All cross sections are $d\sigma/dt$ in $\mu\text{b}/\text{GeV}^2$; errors are statistical only.)

Meson	π^+	π^+	π^+	π^+	π^+	$K^+\Lambda$
k(GeV)	8	8	8	8	8	16
$-t(\text{GeV}^2)$	~ 0.003	0.010	0.039	0.169	0.454	0.043
H(CH ₂ -C)	1.06 ± 0.11	0.79 ± 0.03	0.62 ± 0.02	0.50 ± 0.02	0.265 ± 0.012	0.027 ± 0.004
Be	---	---	---	1.39 ± 0.04	---	0.14 ± 0.01
C	1.87 ± 0.16	1.48 ± 0.05	1.54 ± 0.03	1.63 ± 0.03	1.05 ± 0.05	0.20 ± 0.01
Al	---	---	---	2.50 ± 0.08	---	0.28 ± 0.01
Cu	---	3.60 ± 0.29	3.76 ± 0.19	4.28 ± 0.16	2.62 ± 0.33	0.53 ± 0.03
Ag	---	---	---	5.53 ± 0.27	---	1.07 ± 0.07
Pb	---	---	---	6.66 ± 0.62	5.59 ± 1.04	1.18 ± 0.10

Meson	$K^+(\Lambda+\Sigma)$	π^+	π^+	π^+	π^+	π^-
k(GeV)	16	16	16	16	16	16
$-t(\text{GeV}^2)$	0.043	~ 0.010	0.040	0.153	0.443	0.153
H(CH ₂ -C)	0.056 ± 0.007	0.171 ± 0.009	0.144 ± 0.005	0.114 ± 0.007	0.066 ± 0.004	0.0007 ± 0.0013
Be	0.31 ± 0.01	0.230 ± 0.015	0.258 ± 0.007	0.308 ± 0.015	0.239 ± 0.014	0.131 ± 0.005
C	0.38 ± 0.01	0.302 ± 0.013	0.346 ± 0.007	0.391 ± 0.007	0.298 ± 0.017	0.124 ± 0.004
Al	0.62 ± 0.03	0.554 ± 0.038	0.492 ± 0.014	0.555 ± 0.021	0.44 ± 0.03	0.210 ± 0.014
Cu	1.22 ± 0.07	0.81 ± 0.12	0.83 ± 0.04	0.70 ± 0.11	0.85 ± 0.08	0.38 ± 0.03
Ag	1.64 ± 0.12	---	1.19 ± 0.07	1.12 ± 0.11	0.92 ± 0.13	0.44 ± 0.05
Pb	2.8 ± 0.2	---	1.22 ± 0.11	1.75 ± 0.20	1.29 ± 0.31	0.68 ± 0.08

fects are to a good approximation independent of A .

Changing the radius parameter c by $\pm 0.06A^{1/3}$ F changes w by ± 0.08 ; $\Delta a = \pm 0.1$ F 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 ± 0.3 in the ρ and ω 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 VDM. The large energy dependence predicted by this model is not seen in the preliminary results on γA total cross sections,⁶ in incoherent ρ^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 Yennie⁸ 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 old notions of simple vector dominance do not work.

Cross sections for π^- photoproduction were

measured at 16 GeV, $-t = 0.16$ GeV²; the results are shown in Fig. 2(a). The π^-/π^+ 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; χ^2 for the hypothesis that the ratio is independent of A is 7.5 for 6 degrees of freedom.

Single pions come predominantly from the nuclear surface; a pion produced deep inside the nucleus has a much smaller probability of escaping without inelastic collisions. This makes the π^-/π^+ 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 differences in radii ($c_n - c_p$) for Ag and Pb are, respectively, -0.25 ± 0.4 and -0.7 ± 0.4 F. Assuming equal radii, the differences in skin thickness ($a_n - a_p$) are, respectively, -0.15 ± 0.2 and -0.3 ± 0.2 F. The Pb result is consistent with the calculation of Bethe and Siemens¹¹ which gives a smaller neutron radius than proton radius, but is not consistent with one of the conventional interpretations of K -me-

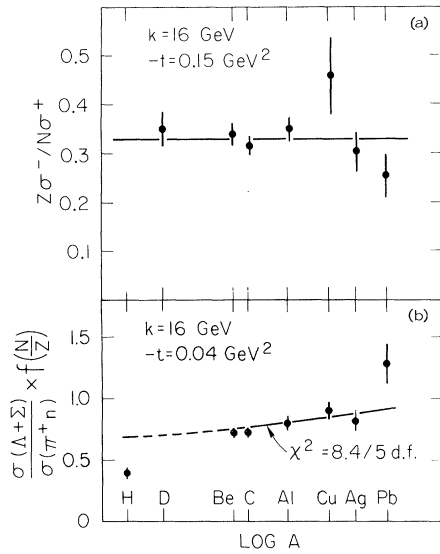


FIG. 2. (a) The A dependence of the ratio

$$\frac{N^{-1}d\sigma(\gamma A \rightarrow \pi^- A^*)/dt}{Z^{-1}d\sigma(\gamma A \rightarrow \pi^+ A^*)/dt},$$

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

$$\frac{d\sigma(\gamma A \rightarrow K^+(\Lambda + \Sigma) + \text{nuclear stuff})}{d\sigma(\gamma A \rightarrow \pi^+ A^*)},$$

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 $\sigma(KN) = 17$ mb and $\sigma(\pi N) = 26$ mb.

sonic x-ray data in terms of neutron radius or skin thickness considerably larger than that of the proton distribution.¹² The π^-/π^+ ratio may also give information on proton-neutron correlations.¹³

The A dependence of K^+ photoproduction was measured at $-t = 0.043$ GeV² and $k = 16$ GeV. Because of the small separation between the Λ and Σ steps and the smearing effects of the nucleon momentum in the nucleus, the Λ and Σ 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 Λ and Σ thresholds. The fitted Λ and $\Lambda + \Sigma$ cross sections are given in the table; the errors on the Λ given in the table do not include Λ - Σ correlations.

Direct comparison of the A dependence of the K^+ and π^+ data is not possible since K^+ can be produced from neutrons (in association with a Σ^-) as well as from the proton ($\Lambda + \Sigma^0$). In an auxiliary experiment we determined that $\Sigma^-/(\Lambda$

$+ \Sigma^0) = 0.53 \pm 0.05$ from single nucleons. Then,

$$\begin{aligned} \frac{d\sigma}{dt}(\gamma A \rightarrow K^+(\Lambda + \Sigma^0)) \\ = \frac{1}{1 + 0.53(N/Z)} \frac{d\sigma}{dt}(\gamma A \rightarrow K^+(\Lambda + \Sigma^0 + \Sigma^-)). \end{aligned}$$

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

Since the VDM has failed to fit the π^+ data, we have also used a less detailed model for the K data in which the incoming γ ray and outgoing K meson are assumed to have attenuation cross sections of σ_γ and σ_K in nuclear matter. A_{eff} is defined by the expression

$$A_{\text{eff}}/A = \sigma(A)/[N\sigma_n + Z\sigma_p],$$

where N and Z are the number of neutrons and protons in the nucleus A . A_{eff} is given in terms of σ_γ and σ_K in the impact parameter model as

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

where ρ 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 VDM.

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answer was large giving an average $w=0.62$.

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STUDY OF THE REACTION $K^-n \rightarrow \Lambda\pi^-$ AT 3.9 AND 3.6 GeV/c: TEST OF EXCHANGE DEGENERACY IN THE t REGION AND AN OBSERVATION OF A BACKWARD PEAK IN THE u REGION*

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Angular distributions in the low- $|t|$ region in the reaction $K^-n \rightarrow \Lambda\pi^-$ and in the line-reversed reaction $\pi^-p \rightarrow \Lambda K^0$ and from other complementary experiments do not support the predictions of exchange degeneracy between the $K_{1/2}^*(890)$ and the $K_{1/2}^*(1420)$ up to $s \sim 11$ GeV². In the low- $|u|$ region of the reaction $K^-n \rightarrow \Lambda\pi^-$ at 3.9 GeV/c, we observe a peak with a slope of 10 ± 3 GeV⁻² followed by a valley from $u = -0.15$ to -0.4 GeV². A simple Regge-pole fit to this backward-scattering region using the N_α trajectory is presented.

The purpose of this Letter is to present (I) an experimental test of the idea of exchange degeneracy between the $K_{1/2}^*(890)$ and the $K_{1/2}^*(1420)$ trajectories from the reaction $K^-n \rightarrow \Lambda\pi^-$ and the line-reversed reaction $\pi^-p \rightarrow \Lambda K^0$, and (II) an observation of a backward peak followed by a valley from $u = -0.15$ to -0.4 GeV² in the reaction $K^-n \rightarrow \Lambda\pi^-$ at 3.9 GeV/c.

The $K^-n \rightarrow \Lambda\pi^-$ data at 3.9 and 3.6 GeV/c come from an exposure of K^- mesons in the Brookhaven National Laboratory 80-in. deuterium-filled bubble chamber. Approximately 240 000 pictures were analyzed to yield 917 events at 3.9 GeV/c and 239 events at 3.6 GeV/c in this reaction.¹ Figure 1 is the distribution in cosine of the angle between the incident K^- and the outgoing π^- in the total c.m. system at 3.9 GeV/c. A strong forward ($\hat{K}^- \cdot \hat{\pi}^- \approx +1$) peak as well as

a pronounced backward ($\hat{K}^- \cdot \hat{\pi}^- \approx -1$) peak are evident. We shall first consider the forward scattering, and then the backward scattering.

(I) Forward scattering.—For small values of four-momentum transfer squared (t) between incident K^- and outgoing π^- , the $K^-n \rightarrow \Lambda\pi^-$ amplitude is expected to be dominated by the exchange of the $K_{1/2}^*(890)$ trajectory (odd-signature factor) and the $K_{1/2}^*(1420)$ trajectory (even-signature factor). According to Regge-pole theory,² the s -channel amplitude A_+ for $K^-n \rightarrow \Lambda\pi^-$ and the u -channel or line-reversed amplitude A_- for $\pi^+n \rightarrow \Lambda K^+$ (or $\pi^-p \rightarrow \Lambda K^0$ via charge symmetry) can be written for small t as

$$A_{\pm}(s, t) = \beta_1(s, t) (1 + e^{-t\pi\alpha_1(t)}) \pm \beta_2(s, t) (1 - e^{-t\pi\alpha_2(t)}), \quad (1)$$