Measurement of Shadowing in Photon-Nucleus Total Cross Sections from 20 to 185 GeV

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We have measured total hadronic photoproduction cross sections on carbon, copper, and lead. Tagged-photon energies ranged from 20 to 185 GeV for copper and from 45 to 82 GeV for carbon and lead. The energy and A dependence of shadowing were computed by comparing these results to the hydrogen cross section as measured nearly simultaneously with the same apparatus. We observed somewhat more shadowing than did most experiments at lower photon energies.

The photoproduction cross section from complex nuclei should be less than the sum of individual nucleon cross sections because (naively) some nucleons "shadow" others by absorbing out the hadronic part of the photon beam. This effect has been observed in photoproduction by real photons of up to 18 GeV.[1-6] Although the results of Ref. 1 disagreed with the vector-meson-dominance (VMD) model used in that paper, it is possible to find models[7] that do give reasonable agreement with the shadowing observed in photoproduction. VMD models do, however, have difficulty accounting for the rapid decrease of shadowing when the photons become slightly spacelike.[8] More data will be useful for suggesting the direction in which models must be elaborated.

We have measured the dependence of the total photoproduction cross section on A, the atomic weight of the target nucleus. One reason for doing so was to get a more accurate measurement of shadowing than has been hitherto possible. The cross section is easier to measure at high energies and our apparatus was designed to achieve the very high precision needed for detecting the small energy dependence of the hydrogen cross section.[9] Another reason for doing this measurement was to extend the energy range of shadowing data. Such an extension could, for example, show effects of higher-mass states. The higher the mass of a vector state, the higher the photon energy must be in order that the state contribute to shadowing. In fact, neutron and K_L cross sections on nuclei do show an increase in the amount of shadowing with increasing energy.[10-12] This increase can be interpreted as an effect of "inelastic screening"[13] of the forward scattering amplitude, in which an incident hadron diffractively dissociates (into a possibly higher-mass state) at one point within the nucleus and recombines at another. In VMD calculations of shadowing, this would correspond to including off-diagonal terms.

The measurement was performed in the Fermilab tagged-photon beam. Tagged photons were produced from copper radiators of 6 and 15 mils (0.0107 and 0.0267 radiation lengths). The beam, detection apparatus, and trigger were the same as used in a measurement of the total photoproduction cross section on hydrogen.[9] However, the hydrogen target was replaced by carbon, copper, and lead targets—each a rectangle larger than the beam and each of approximately 0.1 radiation length in thickness. These targets were mounted in a vacuum box so that each could be rotated into the beam. An empty target slot permitted measurement and subtraction of the rate of hadronic interactions taking place outside the target.

Data were collected for each target with an electron beam energy $E_0 = 90$ GeV, and for copper alone with E_0 values of 40, 60, 135, and 200 GeV. For each E_0 the tagged-photon spectrum was divided into six bins whose mean energies spanned the range from 50% to 91% of E_0.

The analysis procedures were nearly identical to those of Ref. 9. All cuts used in the solid-target analysis to separate electromagnetic from hadronic events were identical to the cuts used in the hydrogen analysis programs.

Pair production could be a much more serious problem for solid targets than for hydrogen because the ratio between pair and hadronic cross sections is so much larger. However, the solid-target statistical errors were much larger than the corresponding hydrogen errors, so that larger pair contaminations could be allowed before systematics became important. Furthermore, pairs produced from a solid target tend to have both particles at wide angles even more rarely than for hydrogen[14] and were therefore easier to separate from hadronic events. Finally, the analysis consisted largely of finding methods for unambiguously distinguishing hadronic and electromagnetic interactions, then making various checks to find and correct for events of varying degrees of ambiguous events, but such corrections were typically smaller than the size of the statistical errors displayed in our results.

Various checks were made of the validity of our methods of data collection and analysis:

(1) Were there serious errors in the target thickness or beam intensity? A scaled-down trigger for pairs was taken and the pair cross section was measured. To within statistical errors (typically 2%) the cross section agreed with that computed by Tsai[15] for all targets and energies.

(2) Have we made the right corrections for the finite-thickness radiators? Because two photons could be radiated by one electron, we had to make corrections amounting to typically 1.2% for the 6-mil radiator and 2.6% for the 15-mil radiator. We took data with a copper target and $E_0 = 90$ GeV for both 6- and 15-mil radiators. After correction, the difference between the two results was (0.6 ± 2.2)%. The hydrogen data gave a much more stringent check of the accuracy of the computation.[9]

(3) Were there serious geometrical losses? For a hydrogen target, our detection system was such that anything going forward in the center of mass had to hit a detector. But for heavier nuclei it was kinematically possible for all photoproduced particles to miss all detectors. It has, in fact, been noticed that hadrons tend to be produced at wider angles from complex nuclei than from hydrogen.[16]

As one check that geometrical losses were unimportant, we took part of the copper data with a 90-GeV beam but with the detector system moved closer to the target and modified so that it was geometrically suited for 40 to 60 GeV.[9] The differences between the cross sections for the two geometries showed no statistically significant energy dependence. Averaged over all photon energies, the difference was (0.2 ± 2.4)%. This check also helps decrease the likelihood of neglected pair contamination; the strong forward peaking of pairs would cause any effect of contamination to be strongly dependent on the geometry of the detector system. The overlap of the $E_0 = 90$-, 135-, and 200-GeV data provides a similar check to similar accuracy.

For another check that we did not lose events at large angles, we examined the dependence on the detector geometry and photon energy of the events that fired only our widest-angle detector ($S1$ in Ref. 9). From this dependence we estimate that removal of the outer 80% of the area of $S1$ would have almost always lost less than 0.5% of the observed cross section.

Our results are plotted in Figs. 1–4. The er-

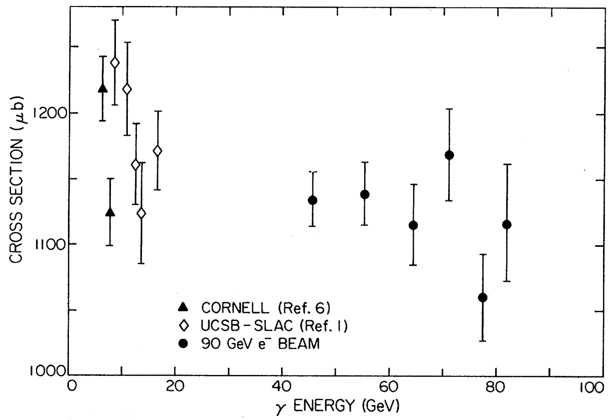

FIG. 1. Photoproduction cross section from carbon.

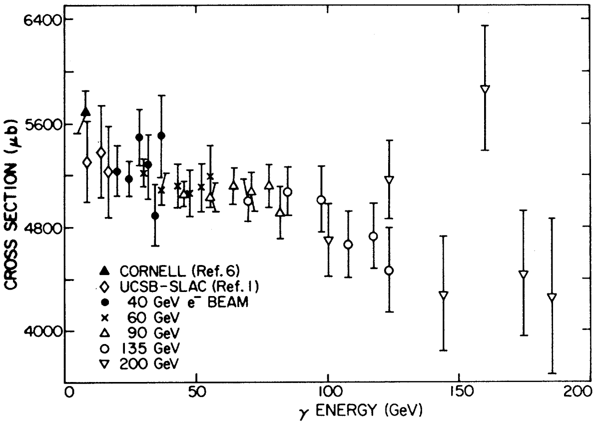

FIG. 2. Photoproduction cross section from copper.

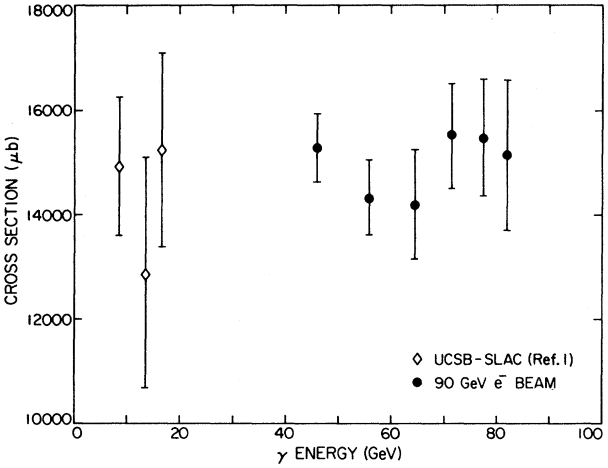

FIG. 3. Photoproduction cross section from lead.

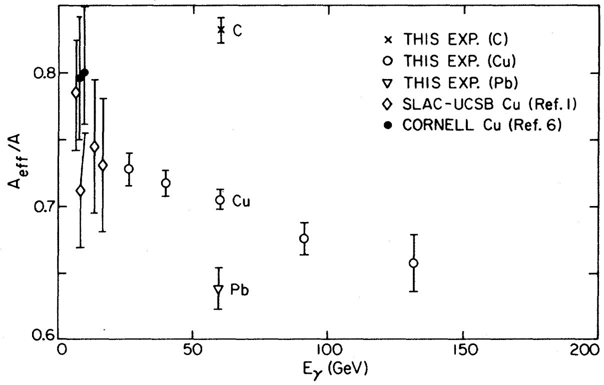

FIG. 4. Energy dependence of $A_{\rm eff}/A$ for carbon, copper, and lead (see text for explanation).

rors shown are statistical; we estimate the systematic errors to be $^{+1.3}_{-0.8}\%$ for carbon and copper, and $^{+2.4}_{-1.1}\%$ for lead. Figures 1–3 show our carbon, copper, and lead cross sections, respectively, as compared with measurements made at Stanford Linear Accelerator Center[1] and Cornell University.[6] Our copper data, which extend to lower energies, match up well with lower-energy data; the cross section falls with energy. Figure 4 shows the amount of shadowing, and requires more explanation.

We would like to be able to display $A_{\rm eff}/A$, defined as the ratio between the photoproduction cross section of a nucleus of Z protons and N neutrons and the sum of the individual cross sections of the constituent nucleons. For the proton cross section we fitted the results of Ref. 9 with a curve of the form $\sigma_{\gamma p} = A + B \ln E_\gamma + C/\sqrt{E_\gamma}$. A, B, and C were chosen to minimize χ^2. A fit of the form $\sigma_{\gamma p} = A' + B'E_\gamma + C'/\sqrt{E_\gamma}$ gave practically the same values of $\sigma_{\gamma p}$. The coefficients of the fits are shown in Table I. Since we do not have data at our energies for a neutron target, we used the fact that lower-energy measurements of the proton-neutron difference are consistent with[1]

$$\sigma_{\gamma p} - \sigma_{\gamma n} = (18.3 \pm 6.1\ \mu\text{b GeV}^{1/2})/\sqrt{E_\gamma}.$$

Although the extrapolation of this formula to our energies is rather uncertain, the proton-neutron difference is a small effect. For example, if we completely neglected the proton-neutron difference, the computed ratio would be changed by about 1% for 60-GeV photons on a nucleus with half protons and half neutrons.

For each target and electron beam energy, the data from different E_γ bins were averaged together before computing the ratio shown in Fig. 4. The E_0 dependence of our systematic errors is expected to amount to only ± 0.6% between 20 and 185 GeV. Also shown in Fig. 4 are several Cu points from Refs. 1 and 6, normalized in a corresponding way to the present data.[17] The tendency of the copper cross section to fall over an energy range in which the hydrogen cross section is rising results in the increase of shadowing with energy.

Current VMD models do not show an increase in shadowing at high energies.[7] The fact that "inelastic screening" successfully explains what

TABLE I. Fits used for the hydrogen data.

Form of the fit	A	B	C	χ^2/d.f.[a]
$A+B\,E_\gamma + C/\sqrt{E_\gamma}$	103.6 ± 1.1	0.0636 ± 0.0074	51.8 ± 4.3	1.45
$A+B\ln E_\gamma + C/\sqrt{E_\gamma}$	49.2 ± 7.1	11.1 ± 1.2	151.8 ± 15.0	1.23

[a] Degrees of freedom.

would otherwise be a surprisingly low cross section for neutron and K_L cross sections on nuclei suggests that off-diagonal terms may be important. Models such as that of Ditsas and Shaw[18] have only near-diagonal terms. Although those terms are large, they do not lead to a significantly different energy dependence of shadowing from diagonal VMD.[7] Hence our data suggest the need for a more complex generalized off-diagonal VMD model.

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Upper Limit for the Decay $\mu^+\to e^+\gamma$

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An examination of 3.6×10^{10} μ^+ decays yields an improved upper limit for the branching ratio $\Gamma(\mu^+\to e^+\gamma)/\Gamma(\mu^+\to e^+\nu_e\bar{\nu}_\mu) < 1.9\times10^{-10}$ with 90% confidence.

The apparent absence of neutrinoless decay[1-4] modes of the muon, $\mu^+\to e^+\gamma$, $\mu^+N\to e^\pm N$, $\mu^+\to e^+e^+e^-$, and $\mu^+\to e^+\gamma\gamma$, and the observation of separate muon and electron neutrinos[5] has lent strong support to the concept of lepton-flavor conservation. Nevertheless, the conservation laws