Experimental Study of Nuclear Shadowing in Photoproduction

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The total cross section for hadron production by high-energy photons has been measured from a number of nuclei ranging from hydrogen to uranium. Some shadowing is observed at a level considerably less than predicted by conventional vector-meson dominance but consistent with a modified theory. The energy dependence predicted by vector-meson dominance is observed. The shadowing in heavy nuclei shows a smooth transition from electroproduction to photoproduction.

The phenomenon of "shadowing" of nucleons in complex nuclei is expected to be seen in the hadronic interaction of photons, presumably arising from a hadronic component of the photon. In other words, A_{eff}, the effective number of nucleons participating in the reaction is expected to be less than A, the number of nucleons in the target nucleus.

Some shadowing has been observed in measurements of the total cross section of real photons on complex nuclei.[1-3] Electroproduction experiments have shown a much smaller effect.[4,5] In particular, our previous experiment[5] at $Q^2 = 0.1$ GeV^2 showed substantially less shadowing than had been observed at $Q^2 = 0$ and also less than predicted by a form of vector-meson dominance (VMD).[6] A rapid change in shadowing between $Q^2 = 0$ and $Q^2 = 0.1$ GeV^2 is not compatible with VMD.

In an attempt to clarify this situation at low Q^2 we have completed a new measurement of the total hadronic cross section on hydrogen, deuterium, and complex nuclei, using a tagged photon beam in the energy range 1.0–10.5 GeV. An electron beam was extracted from the Cornell 12-GeV synchrotron and steered onto a tantalum radiator 0.002 radiation lengths (r.l.) long. Photons were tagged by deflecting the corresponding energy-degraded electrons in a magnet and detecting them with sixteen tagging scintillation counters. Charged particles were eliminated by passing the beam through a series of collimators, sweeping magnets, and thin veto counters. (As with other veto counters not yet described, the veto signals were not employed in the triggering which determined those events recorded for subsequent analysis.) Ultimately, all events were rejected for which a charged particle was detected upstream of the target.

To detect hadrons in the final state the target was surrounded by scintillation counters as shown schematically in Fig. 1. At large angles ($\gtrsim 350$ mrad from the beam) particles were detected in scintillation counters forming a box around the target. At forward angles in the range

$$30 \text{ mrad} < \theta < {\sim}450 \text{ mrad}$$

the detector consisted of two large disks of scintillator each viewed by 36 phototubes. The positions of minimum ionizing particles in the disks could be measured with an accuracy of ± 2 cm (± 20 mrad). At all angles greater than 30 mrad the counters were preceded by 2 r.l. of lead to ensure good π^0 detection.

Angles less than 30 mrad were covered by an array of four counters directly in the beam, approximately 4 m downstream of the target. These counters are VE, a thin scintillator ($0 < \theta < 12$ mrad), $V0$, a thin scintillator (12 mrad $< \theta < 30$ mrad), VG a scintillator with lead converter in front of it (12 mrad $< \theta < 30$ mrad), and VP an 18-r.l. shower counter ($0 < \theta < 12$ mrad).

The event trigger was a coincidence between a tagged photon and a "hadron" signaled by a count

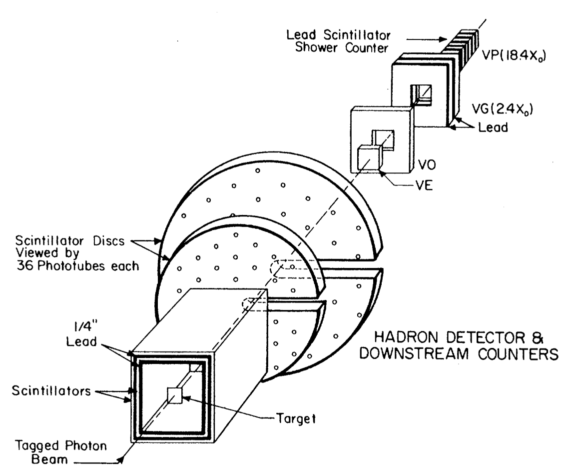

FIG. 1. Schematic view of the hadron detector and the downstream veto counters.

in the hadron counters surrounding the target. For all such triggers, information from all counters was recorded on tape.

We enumerate the various possibilities when a photon beam is incident on the target and describe how the detector responds: (i) Most photons pass through the target without interacting and produce a large pulse in the shower counter *VP*. These give no "hadron" signal and hence no trigger. (ii) Several percent of the photons give an electron-positron pair, but usually both particles emerge at angles so small as to give no "hadron" count and hence no trigger. (They do count in *VE* which is useful as a monitor.) (iii) A small fraction of e^+e^- pairs yield a trigger because one of the pair is produced at, or multiply scatters to, an angle large enough to count in the hadron counters. Such an event gives a trigger, but normally the other member of the pair (which usually retains most of the energy of the photon) gives a large pulse in the shower counter *VP* as well as counting in *VE*. (iv) Occasionally both members of electron pairs emerge at large angles and give two "hadron" tracks and no counts in the downstream veto counters. They masquerade as hadronic events but can be studied further on a statistical basis as they are concentrated at small angles. (v) Truly hadronic events usually give at least one count in the hadron counters and usually no count in the downstream counters. The apparatus provides an approximate multiplicity in addition to information on the particle directions, which is important in extracting the correct total cross section.

Data were obtained from hydrogen and deuterium targets of thickness 0.02 r.l. and from carbon, aluminum, copper, silver, gold, and uranium targets, all of about 0.08 r.l. Also, for selected complex nuclei, data were taken for various thicknesses from 0.02 r.l. to 0.2 r.l. The tagging system tagged electron energies in the band

$$1.08 < E_e < 4.40 \text{ GeV}.$$

Data were taken with incident electron energies, E_0, of 5.0, 5.65, 6.95, 8.90, and 11.50 GeV and the corresponding photon energies, k_γ, were in ranges given by

$$(E_0 - 4.40) < k_\gamma < (E_0 - 1.08) \text{ GeV}.$$

For all targets the flux of photons incident on the target was determined by monitoring coincidences between tags and the downstream shower counter *VP*. Samples of data were recorded with only the photon tag required. These were used to determine the relative energy spectrum of incident photons.

At all energies the trigger rate was dominated by events of type (iii) with a soft electron or positron scattering to an angle greater than 30 mrad. These were easily rejected by their pulses in *VE* and *VP*. This procedure resulted in the rejection of some hadronic events. For hydrogen and deuterium, since the electron-pair rate was small, it was possible to study this hadronic inefficiency by the pulse-height distribution in *VP*. The effect of rejecting events with forward-going particles ($\theta < 12$ mrad) is to introduce a hadronic inefficiency of 8% at $k_\gamma = 10$ GeV and 2% at $k_\gamma = 2$ GeV, for hydrogen.

For high-Z elements, there is a significant rate for events of type (iv) which give no counts in the downstream veto counters. Using angular information from the two scintillator disks, we made a further cut around the beam, rejecting all pair-like (observed multiplicity of one or two) events which are totally confined to a forward cone of angle θ_c. In previous experiments a similar cut was effected by means of a hole in the detector. The value used was chosen such that a Monte Carlo estimate of the residual e^+-e^- contamination outside the cut was less than 2% of the observed hadronic cross section. This procedure has the disadvantage that it results in significant inefficiency for detecting high-energy ρ^0 photoproduction. Since a large fraction of this cross section is coherent, an incorrect A dependence could possibly be introduced into our measurements. Using published results for ρ^0 photoproduction,[7-9] an optical model for interpolation, and the known acceptance of our detectors we have studied this effect and corrected our data. In the worst case (high energy) the A dependence of the ρ^0 total cross section differs but little from the total photon cross section and the correction to our shadowing factor is never more than 3%. The correction to the total cross section can be as high as 12%. For hydrogen, where the electron-pair rate is small and ρ^0's can be explicitly counted, the magnitude of this correction was verified. Furthermore, after correction, all our cross sections were insensitive to changes in θ_c of a factor of 2 either way.

Various possible sources of error of an instrumental nature have been considered. Because of the good duty factor of the synchrotron, accidentals were negligible. An individual hadron track had probability less than a few percent of being

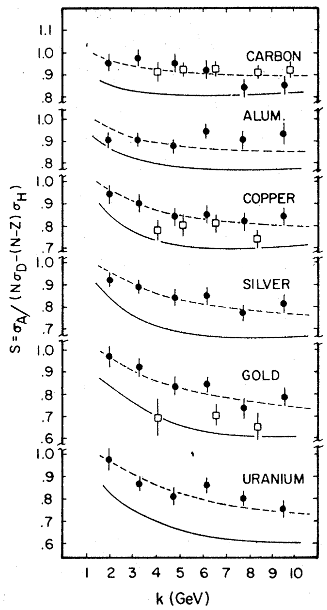

FIG. 2. Observed and predicted shadowing factors, S. The solid points are the results of this experiment. The open points are from Ref. 3. The solid curves are a conventional VMD calculation (Ref. 6). The dashed curves are the result of incorporating "self-absorption" (Ref. 10).

accidental, and most hadron events had multiple tracks. For further safety the beam intensity was adjusted to keep this rate roughly constant for all targets. It can be pointed out that accidental problems are most serious for the heaviest nuclei. This can account for good agreement among experiments for small nuclei (as is observed) but disagreement on heavy nuclei. Some worst-case empty-target rates were hydrogen (10%), carbon (2%), and gold (22%). About 10% of the photon "tags" were "false"; i.e., accompanied by no signals in any of the downstream counters. Most of these (~8%) were due to room background in the tagging counters. The other 2% were present only with the photon radiator in place. False tags could cause errors due to accidentals in the hadron counters, since no veto count can be present to reject the event. Quantitatively, though, this effect is negligible.

Another check we have made is to extract the total electron-positron pair-production cross section from our data. Over the range 1–10 GeV and from all targets our cross sections agree within 2% with the theoretical cross sections of Tsai.[10] These results have been described in a separate paper not yet published.

The amount of shadowing can be expressed as the ratio

$$S' = \frac{\sigma_A}{N\sigma_n + Z\sigma_p} \tag{1}$$

or as the ratio

$$S = \frac{\sigma_A}{N\sigma_D - (N-Z)\sigma_H}, \tag{2}$$

where p, n, H, and D refer, respectively, to proton, neutron, hydrogen, and deuterium. Z is the number of protons and N the number of neutrons. In the absence of shadowing the deuteron cross section would be the sum of the proton and neutron cross sections and S and S' would be equal. It is natural to express theoretical calculations in the form S' but we present our results in the form S as that is a ratio of our actual measured quantities. Deuteron shadowing effects have been incorporated into theoretical predictions for comparison with the data.

The results are shown in Fig. 2 and in Table I. Errors shown are statistical. For the total cross sections there is a further systematic uncertainty of 4%. For the shadowing factor, S, the systematic error is small compared to the counting statistics. The hydrogen cross sections agree well

TABLE I. Total hadronic cross sections per nucleon (in μb).

	k = 2.00 (GeV)	3.27 (GeV)	4.81 (GeV)	6.21 (GeV)	7.79 (GeV)	9.51 (GeV)
H	143.2 ± 2.7	126.8 ± 2.2	121.8 ± 2.2	115.9 ± 2.2	123.8 ± 2.4	114.1 ± 2.8
D	132.6 ± 2.5	119.8 ± 2.0	122.0 ± 2.2	112.3 ± 2.1	116.0 ± 4.4	107.8 ± 2.4
C	125.7 ± 5.8	116.6 ± 5.3	115.5 ± 5.5	103.9 ± 4.7	97.0 ± 4.6	91.7 ± 4.8
Al	118.3 ± 4.6	107.6 ± 3.6	106.4 ± 4.0	105.7 ± 4.1	104.0 ± 5.0	100.0 ± 6.1
Cu	124.1 ± 4.9	107.2 ± 3.8	102.5 ± 4.1	95.6 ± 4.1	94.9 ± 3.9	89.5 ± 4.4
Ag	120.5 ± 4.5	105.6 ± 3.9	102.9 ± 4.1	95.6 ± 3.9	88.5 ± 4.1	86.9 ± 4.4
Au	126.6 ± 5.4	108.0 ± 5.3	101.7 ± 4.9	94.2 ± 4.4	84.1 ± 4.1	82.7 ± 4.7
U	127.3 ± 6.6	103.3 ± 4.0	99.2 ± 4.2	96.0 ± 4.3	91.6 ± 4.2	79.9 ± 4.4

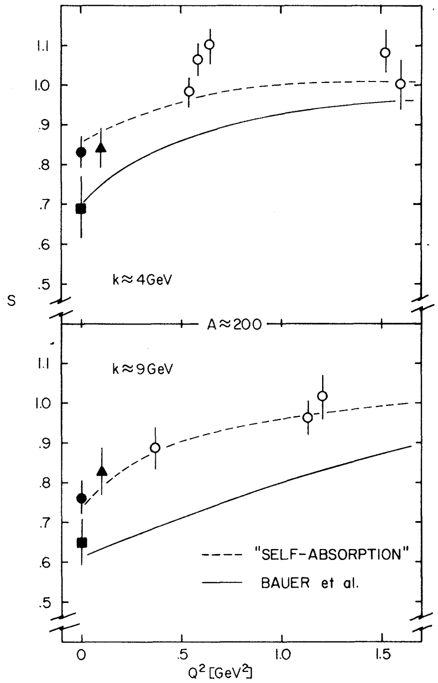

FIG. 3. Dependence of the shadowing factor S on Q^2 for $A \simeq 200$. The curves are labeled in the caption to Fig. 2. Experimental points are filled circle, this experiment, Au; filled square, Ref. 3, Pb; filled triangle, Ref. 5, Ta; and open circles, Ref. 4, Au.

with those of Armstrong *et al.*[2] and Caldwell *et al.*[3] As predicted by theory, the value of S decreases with increasing energy for all complex nuclei. But the amount of shadowing is substantially less than predicted by VMD (solid curves).[6] A modified optical model[11] which incorporates shadowing in individual nucleons ("self-absorption") fits the data well (dashed curves). Our data for heavy nuclei do not agree with previous measurements[3] (though by only two of their standard deviations). In particular, in Fig. 3, which shows the Q^2 dependence of S for $A \sim 200$, our data indicate a smooth transition from $Q^2 = 0$ to the electroproduction results.

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