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Total Hadronic Photoabsorption Cross Sections of Nuclei for Photons in the GeV Energy Range

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The total hadronic photoabsorption cross sections of a number of nuclei (C, Al, Cu, Nb, Sn, Ta, Pb) have been studied in detail using a tagged photon beam over the energy range 1.7–4 GeV. The results are described, and compared with models of photoabsorption.

I. INTRODUCTION

The hadronic nature of the interactions of photons in the GeV energy region with nucleons has been studied by measuring the total photoabsorption cross section (σ_T) for hadron production in hydrogen[1,2,3] and deuterium.[1,2,4] Typically, the value of the total cross section in hydrogen in this energy region is ~120 μb, which, in terms of nuclear matter, would imply a mean free path for interaction of the order of hundreds of fermis. Consequently, the photoabsorption cross section for nuclei might, naively, be expected to increase linearly with A, and a measurement of σ_T for complex nuclei is of interest to check this conclusion.

On the other hand, there is now a considerable body of evidence that many of the features of the photoproduction of hadrons off nucleons can be accounted for by the vector-meson dominance (VMD) model[5,6] in which the hadronic interaction of the photon and nucleon is mediated through a vector meson (ρ, ω, ϕ). This meson has a strong interaction with the nucleon, and consequently, one is led to expect some overshadowing of the interior nucleons by other surface nucleons, such that σ_T varies as A^x, where x could be as low as 0.7, this value being dependent upon the detailed model for the absorption of the photon and upon the photon energy. Some measurements[7,8] have already been reported from other laboratories which indicate that $x \sim 0.9$, i.e., the exponent lies in value between that predicted by the VMD model and that based on zero shadowing of the nucleons. However, essential features of the theory such as the distinct increase of shadowing with energy have not so far been shown to exist. Furthermore, inelastic electron-scattering experiments on nuclei[9] at low q^2 have shown little evidence of the shadowing predicted by VMD.

This paper reports upon an experiment which has been done at the Daresbury Nuclear Physics Laboratory using a tagged photon beam,[10] in which the total cross section for the hadronic absorption of photons $\sigma_T(\gamma A)$ has been measured for a series of nuclei spanning the periodic table. The present investigation examines the photon energy region 1.7–4 GeV. Specifically, we examine the behavior

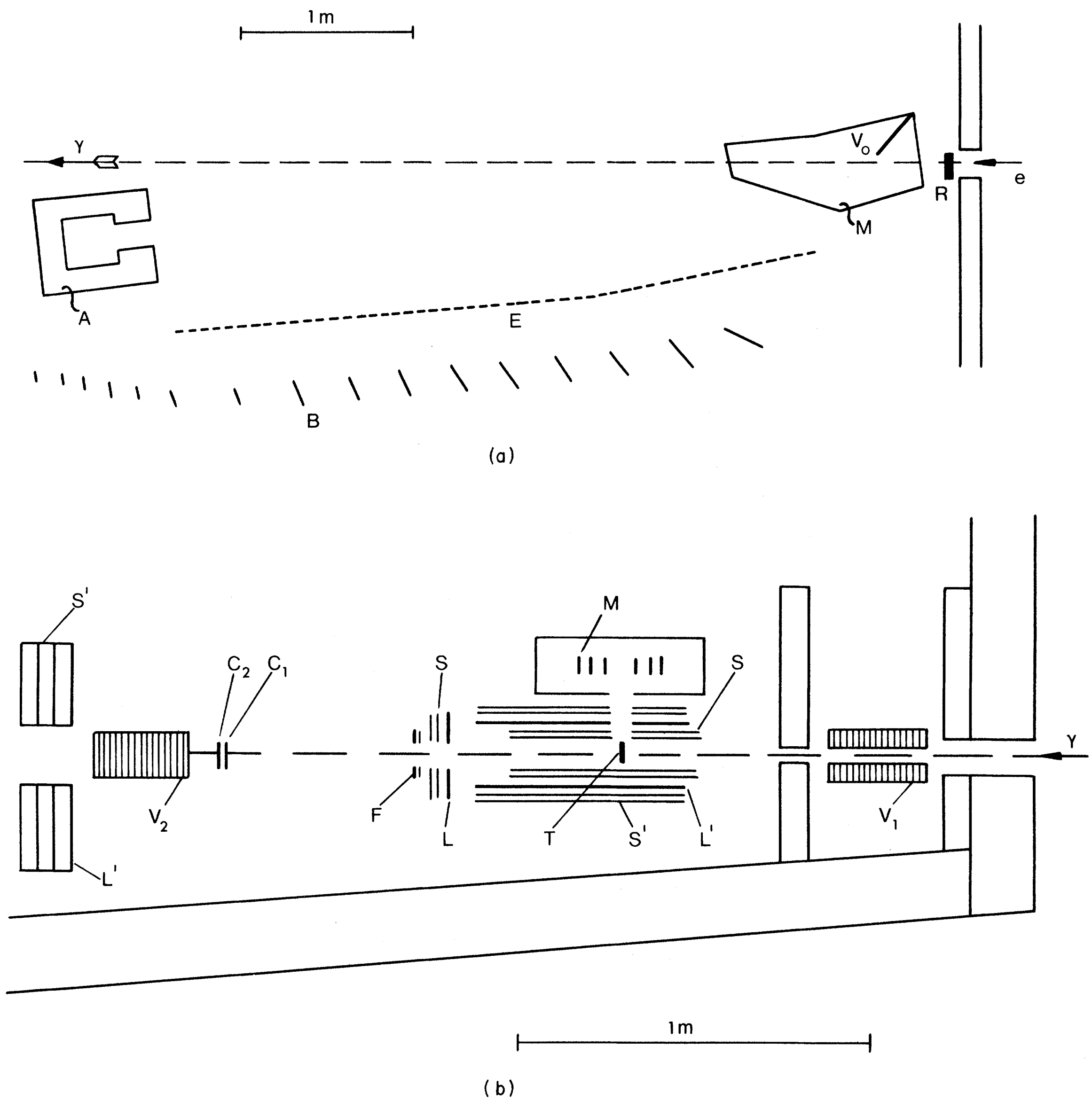

FIG. 1. Schematic diagram of the detection apparatus: (a) The electron beam of fixed energy from the synchrotron radiates in the target R ($\frac{1}{200}$ radiation length); an electron's momentum after radiating is measured by the deflection in the magnetic field M and its detection by the scintillation counters E and B. Thus a coincidence EB denotes an electron of a given momentum and as such serves to "tag" the energy of the radiated photon. A is a beam stop. V_0 is a veto counter to reduce effects of pair production in R (see Sec. III). (b) The tagged photons pass through the hole in the collimator veto counter V_1 to the target disk T, which can be selected by remote control using the mechanism M. Hadronic events produced can be detected in the surrounding paired scintillators S and π^0 scintillators S', L and L' being lead convertors. Electromagnetic events are vetoed by the shower counter V_2 and electron counters C. F are forward-angle counters of varying annular aperture.

of the quantity

$$\frac{A_{\text{eff}}}{A} \equiv \frac{\sigma_T(\gamma A)}{Z\sigma_T(\gamma p)+(A-Z)\sigma_T(\gamma n)} \qquad (1)$$

as a function of atomic number A and photon energy ν, using the previously published cross sections[3,4] for $\sigma_T(\gamma p)$ and $\sigma_T(\gamma n)$.

With regard to the experimental method, it should be mentioned at the outset that the accurate measurement of σ_T for complex nuclei is difficult because of the preponderance of electromagnetic events as Z increases. The ratio of the electromagnetic to hadronic interactions of photons is of order 300 for carbon and 2000 for lead. One has to rely, therefore, very heavily on electronic and other methods of suppressing the unwanted electromagnetic events. The corrections for the higher-Z elements tend therefore to be significant. However, these corrections are manageable, and experimental tests have been made to achieve their evaluation.

II. EXPERIMENTAL METHOD

The apparatus used in these measurements has already been described elsewhere.[3] However, some modifications were made to the equipment to carry out the present investigations. The liquid hydrogen target of the earlier experiment was replaced by solid targets (C, Al, Cu, Nb, Sn, Ta and Pb) in the form of circular disks which were individually mounted on slides and moveable in turn into and out of the photon beam by remote control. The removal of the liquid target and its refrigerator also enabled the efficiency of the system for detecting backward going π^0's to be improved. The new assembly is shown schematically in Fig. 1.

The aim as before was to detect with high efficiency the production of hadrons by the photons, while rejecting with the maximal efficiency, by means of the shower counter V_2 and electron counters C_1 and C_2, events of an electromagnetic character. Because of the prolific nature of these latter events for high-Z elements, C_1 and C_2 were now operated separately as veto counters. The efficiencies of V_2, C_1, and C_2 for vetoing electrons were measured in a subsidiary experiment using a weak electron beam of energy 3.5 GeV. The efficiency of V_2 was found to be at least 99.8%, while those for C_1 and C_2 were 99% and 98%, respectively. From these measurements, it is concluded that the over-all veto inefficiency of these three counters in the main σ_T experiment is 1 part in 10^6. The magnitudes of the resulting corrections due to such efficiencies made in determining σ_T are, therefore, manageably small even in the case of lead (see Sec. III).

The electronic logic and method used was substantially the same as in the earlier work[3] to which the reader is referred for details. The events were recorded on magnetic tape, together with a "flag" pulse to distinguish "real" from "random" events.

Most of the data were taken for tagged photon-beam intensities in the range $5\times10^3-2\times10^4$ photons per second, the lower intensities being used for targets of higher Z. Under these conditions, the random coincidence and veto rates were always kept at a level below 10% of the rate of real events. Some data were also taken at lower photon-beam intensities ($\sim10^3$ photons per second) and these too confirmed the normalizations. Empty-target runs were regularly interspersed with solid-target runs. This could be done conveniently by the remote-control target-changing arrangement without affecting beam conditions.

Data runs were carried out with incident electron-beam energies of 3.5 and 4.6 GeV. With the tagging system spanning 1600 MeV, this allowed regions of overlapping energy to be studied. A summary of the targets and the amount of data taken for each are given in Table I.

TABLE I. Details of targets and total data acquisition.

Target element	Thickness (g cm^{-2})	Events: 3.5-GeV beam (ν=1.65–3.05 GeV)	Events: 4.6-GeV beam (ν=2.75–3.95 GeV)
C	1.38	9000	2500
Al	1.50	6500	5000
Cu	0.69	6000	6500
Nb	0.60	4000	4500
Sn	0.52	3000	1500
Ta	0.47	1500	300
Pb	0.41 (most runs) 0.45	4500	1500
Empty target	...	1500	1000

The counts in each channel of the tagging system were compared frequently with the theoretical bremsstrahlung spectrum expected from the copper radiator of thickness 0.005 radiation length. The tagging rates with radiator out were also often checked against those with radiator in. Because of the dominant nature of electromagnetic processes in targets of higher Z, some corrections could be anticipated and assessed for these. To obtain experimental checks, about a quarter of the data runs with the incident beam of energy 3.5 GeV were carried out using only π^0 counters outside the lead sheath and downstream counters as detectors. About a quarter of the data runs were taken where a lead lining, 6 mm thick, was inserted just inside the inner layer of counters. The shower counter subtended $\pm 3.5°$ at the target center throughout these measurements.

Corrections for events with forward-going products vetoed by the shower counter were determined as described in our earlier papers, by the use of forward-angle counters, F, in Fig. 1.

Analysis of the data tape was carried out on the IBM 360/65 computer on site. Preliminary analysis was done "off-line" during the data taking runs to ensure the correct operation of the equipment.

III. RESULTS AND CORRECTIONS

The yield of hadronic events from the solid targets could be expected to be largely dependent on their mass per unit area. The empty target background yield was roughly equivalent to that of 0.15 $\mathrm{g\,cm^{-2}}$ of carbon, so that for a carbon target the background contributed about 10% of the total event rate. The data obtained for a given target material were collected into energy bins 200 MeV wide and corrections were made for random events and random vetoes. Since low-energy electron contamination, random, and background counts tended to concentrate in the first few channels of the tagging system,[3,4] data from these channels were not included in the final analysis. For the full range of Z, final data were therefore derived for the energy bins: 1.75 ± 0.1 GeV to 2.95 ± 0.1 GeV inclusive, and 2.85 ± 0.1 GeV to 3.85 ± 0.1 GeV, inclusive.

It was first necessary to apply a correction for the hadronic events emitted in the forward cone of the vetoing shower counter, based on the data of the forward-angle counters. The mean values of this in the 3.5- and 4.6-GeV runs were +4% and +6%, respectively. Corrections of order 1 to 2% had to be applied for the absorption of photons by any interactions (predominantly electromagnetic) in the target materials. For the lowest-Z materials, e.g., carbon and aluminum, these were the only noteworthy corrections. For these materials the runs at 3.5 GeV, with and without lead linings, gave essentially similar values for σ_T, confirming that the experiment was working in the correct manner.

For the higher-Z materials several additional corrections have to be applied, generally increasing in magnitude with Z. They arise in large part from the scattering of pairs produced in such targets by lower-energy γ rays. They can be shown generally to be less important if lead linings are used, and measurements carried out at 3.5 GeV quantitatively support the assessments. The corrections to the complete 3.5-GeV data are consequently smaller than those to the 4.6-GeV data. The additional corrections arise as follows:

(i) Double bremsstrahlung in the radiator can produce a low-energy γ ray and a high-energy γ ray which could escape being vetoed. The efficiency of the shower counter for detecting high-energy γ rays has been measured to be 99.8% or greater; its calculated maximum efficiency is 99.95%, so its vetoing action, while very great, is not perfect. Thus accompanying low-energy γ rays (particularly those in the range 5–250 MeV) can produce pairs in a target of high-Z material, which scatter away from the veto electron counters towards the detectors. For lead linings the lower point on the γ-ray energy is necessarily raised and the energy band reduced. Corrections in the case of the target of lead were estimated to lie between −2% and −4%.

(ii) Production of a γ ray and an undetected electron (of energy greater than 1850 MeV), can be followed by pair production in the radiator. Either member of the pair can then radiate a low-energy γ ray, and the electron of this pair can be deflected into the tagging system. The process is third order, and the counter V_0 [see Fig. 1(a)] serves to reduce it. The counter V_0, however, cannot be placed too close to the beam line, and the same low-energy γ rays as in the previous case produce pairs in a high-Z target which scatter. The correction increases with beam energy since faster positrons can more readily avoid V_0. This correction has been evaluated to be −2% and −3% for the runs at 3.5 and 4.6 GeV, respectively, for lead.

(iii) Even for the high-energy γ rays constituting the main tagged beam, there is a chance that both members of the pair produced in a target can pass outside the following electron and shower veto counters. For high-Z targets, the pair-production cross section becomes large enough for this contribution to become significant. This effect is necessarily greater at the lower beam en-

TABLE II. Over-all mean systematic corrections to data.

Target	3.5-GeV beam (ν=1.65–3.05 GeV)	4.6-GeV beam (ν=2.75–3.95 GeV)
C	+7%	+8%
Al	+6%	+7%
Cu	+5%	+4%
Nb	+4%	+2%
Sn	+2%	−1%
Ta	0%	−3%
Pb	−1%	−4%

ergy, but even here in magnitude it is less than 3% for lead.

(iv) Any low-energy electron contamination in a beam can produce low-energy tagged photons. It is essential that this contamination be kept extremely small by careful beam design and beam layout. The ratio of the rates of tagged γ ray in coincidence with the shower counter (and vetoed by V_0, V_1) under radiator "out" and radiator "in" conditions was about 0.5%. The distribution of counts in the tagging counters could be compared in the two cases, and was found to be very similar.

The spatial distribution of counts throughout the tagging system could also be observed with the radiator out, without demanding a pulse from the shower counter in coincidence (i.e., without demanding a tagged γ ray). Comparison with the previous data indicated that the flux of low-energy electrons was at most $\frac{1}{10}$% of the full tagged γ-ray rate. This meant that not more than one electron in 2×10^5 incoming electrons was a "soft" electron. Here again, the same energy γ rays as in (i) and (ii) can be a source of counts. On the basis of these measurements, the corrections amount to −2% and −3% for the runs at 3.5 and 4.6 GeV, respectively, for lead.

For targets of intermediate values of Z, scattering of pairs is reduced, and thus the range of low-energy γ rays capable of causing error is likewise reduced.

Table II lists the mean over-all corrections applied to the raw data for various targets. Applying these corrections to the raw data, one then gets the final results shown in Table III. The statistical errors are given. The additional systematic errors vary from ±3% for carbon to ±4% for lead in the 3.5-GeV beam work, and from ±3% for carbon to ±5% for lead in the 4.6-GeV beam work. Plots of the data with statistical errors are shown in Fig. 2 along with corresponding data from the earlier hydrogen[3] and deuterium[4] work. In applying the above corrections at each data point here, one can show that because of the nature of the processes involved the variation in magnitude of the correction with energy is small and, therefore, the mean value of the correction has been applied.

IV. ANALYSIS AND DISCUSSION

There have been a number of papers dealing with the theory of photoabsorption in nuclei, the basis of which is the notion that a photon turns into some combination of vector meson ρ, ω, and ϕ, and it is the meson which is responsible for the hadronic interaction. This VMD idea has been developed along two lines in connection with total cross sections. One considers that the interactions are

TABLE III. Total cross section (σ_T) in μb, with statistical errors.

ν (GeV)[a]	C	Al	Cu	Nb	Sn	Ta	Pb
1.75±0.1	1590±55	3410±130	7760±340	12 190±600	15 450±850	22 000±2100	23 270±1400
1.95	1480	2990	7620	10 560	14 230	18 600	22 470
2.15	1440	3080	7040	10 920	12 850	19 700	24 650
2.35	1430	2730	7100	10 870	13 310	20 200	22 770
2.55	1330	2940	7690	10 500	12 900	22 300	22 080
2.75	1350	2820	7220	10 500	12 190	21 100	21 880
2.95	1130	2400	6040	8340	10 350	23 300	22 280
Mean	1390±20	2910±50	7210±130	10 550±230	13 040±320	21 000±800	22 800±500
2.85±0.1	1250±75	2910±125	6070±250	9450±500	11 270±900	13 970±2500	18 500±1800
3.05	1270	2680	6480	9200	11 430	13 680	18 100
3.25	1270	2550	5900	9000	10 050	17 270	22 200
3.45	1190	2500	6070	9000	11 420	21 920	21 600
3.65	1090	2390	5900	8650	11 660	13 190	20 500
3.85	1050	2460	6290	9800	9900	27 940	24 300
Mean	1190±30	2580±50	6120±100	9200±200	10 960±370	18 000±1200	20 900±800

[a] For ν=1.75–2.95, electron beam energy was 3.5 GeV. For ν=2.85–3.85, electron beam energy was 4.6 GeV.

dominated by the ρ meson and on this basis one can calculate the effect of ρ dominance assuming that the total cross section for absorption of a ρ meson by a nucleon is energy-independent and equal to 30 mb.[11]

Alternatively, one can use the quark model and deduce an energy dependence of $\sigma_T(\rho p)$ from a knowledge of pion-nucleon cross sections, and in this way obtain a more accurate estimation of the contribution of ρ dominance in photoabsorption. The recent developments in this phenomenological analysis have stemmed from the work of Stodolsky,[12] Bell,[13] Margolis and Tang,[14] von Bochmann *et al.*,[15,16] Brodsky and Pumplin,[11] and Gottfried and Yennie.[6,17] In discussing the data here, we shall draw comparisons with the predictions of the ρ-dominance model, assuming a constant $\sigma_T(\rho p)$,[11] and with the energy-dependent model.[17]

To make such comparisons, we group the data into convenient energy bins, and calculate A_{eff}/A from Eq. (1) for each energy bin using our previously published data[3,4] for $\sigma_T(\gamma p)$ and $\sigma_T(\gamma n)$. A similar procedure has been adopted by Caldwell *et al.*[18] and differs from the earlier theoretical approaches, in which it was assumed that $\sigma_T(\gamma p) \approx \sigma_T(\gamma n)$. The present body of experimental evidence indicates that the ratio $\sigma_T(\gamma n)/\sigma_T(\gamma p)$ lies typically in the region of 0.90 to 0.95 over the photon-energy range 1–4 GeV. The values taken for $\sigma_T(\gamma p)$ and $\sigma_T(\gamma n)$ in the present analysis are

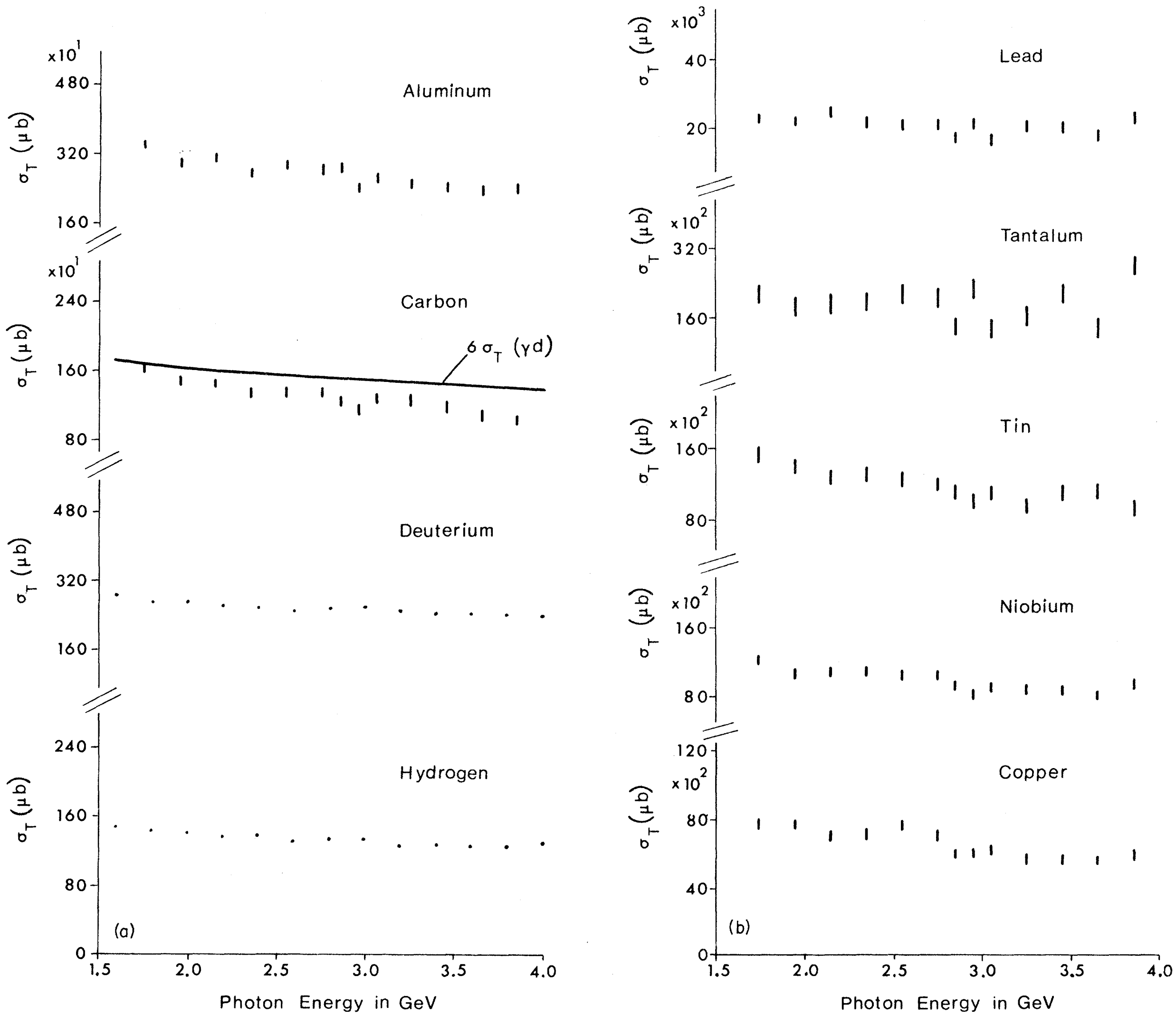

FIG. 2. Total cross section in microbarns of elements for hadron production by γ rays. Hydrogen data Ref. 3. Deuterium data Ref. 4. Others—present experiment. In the case of carbon, the full line shown is the behavior of the cross section $6\times\sigma_T(\gamma d)$.

TABLE IV. Values of A_{eff}/A.

Target	Expected σ_T (μb) ($\sigma_p=137$ μb; $\sigma_n=126$ μb)	Observed mean (statistical errors)	A_{eff}/A (statistical errors)
		3.5-GeV beam ($\nu=1.65$–3.05 GeV)	
$^{12}_{6}C$	1580	1390 ± 20	0.88 ± 0.01
$^{27}_{13}Al$	3550	2910 ± 50	0.82 ± 0.02
$\sim^{63}_{29}Cu$	8260	7210 ± 130	0.87 ± 0.02
$^{93}_{41}Nb$	12 200	$10\,550\pm230$	0.86 ± 0.02
$\sim^{118}_{50}Sn$	15 400	$13\,040\pm320$	0.85 ± 0.02
$^{181}_{73}Ta$	23 600	$21\,000\pm800$	0.89 ± 0.04
$\sim^{207}_{82}Pb$	27 000	$22\,800\pm500$	0.84 ± 0.02
Target	Expected σ_T (μb) ($\sigma_p=129$ μb; $\sigma_n=123$ μb)	Observed mean (statistical errors)	A_{eff}/A (statistical errors)
		4.6-GeV beam ($\nu=2.75$–3.95 GeV)	
$^{12}_{6}C$	1510	1190 ± 30	0.79 ± 0.02
$^{27}_{13}Al$	3400	2580 ± 50	0.76 ± 0.02
$\sim^{63}_{29}Cu$	7920	6120 ± 100	0.77 ± 0.02
$^{93}_{41}Nb$	11 700	9200 ± 200	0.79 ± 0.02
$\sim^{118}_{50}Sn$	14 800	$10\,960\pm370$	0.74 ± 0.03
$^{181}_{73}Ta$	22 700	$18\,000\pm1200$	0.79 ± 0.05
$\sim^{207}_{82}Pb$	26 000	$20\,900\pm800$	0.80 ± 0.04

given in Table IV, together with the mean of $\sigma_T(\gamma A)$ and the calculated values of A_{eff}/A.

The results are shown plotted in Fig. 3 for the elements carbon, copper, and lead, together with the data from other investigations.[7,8] As can be seen, the present data at the lower energies fit smoothly onto the higher-energy data, although statistical error bars are fairly large.

Another way of presenting the data is shown in Fig. 4 where the mean values of A_{eff}/A are plotted versus A for the two photon-energy ranges having mean energies 2.35 and 3.35 GeV. There are two features which require comment:

(i) There is clear evidence that the shadowing is increasing with photon energy in this energy region.

(ii) The general trend of the experimental data suggests that the energy-dependent shadowing does not increase markedly with A after $A\sim12$.

To compare these results with the predictions of VMD models, theoretical curves[11,17] are also shown in Figs. 3 and 4. In connection with the energy-dependent model,[17] use has been made of the optical-model program ELSCAT (R. Spital and D. R. Yennie, private communication) to calculate the mass and energy dependence of the parameter A_{eff}/A. Details of parameters used in these calculations are given in the Appendix.

The shadowing features (i) and (ii) of the data referred to above are broadly in accord with these VMD-model predictions in the photon-energy range studied here. However, there is an indication that the energy-dependent program ELSCAT predicts more shadowing than observed at the lower mean energy of 2.35 GeV. The contribution of ρ dominance as calculated using the quark-model values of $\sigma_T(\rho p)$ may not be wholly realistic for photoabsorption at such low energies. (*Note added in proof.* A further discussion of the photon-absorption process in nuclei is given in the paper by S. J. Brodsky, F. E. Close, and J. F. Gunion [Phys. Rev. D 6, 177 (1972)] where the behavior of the exponent in the slope of $\sigma_T(\gamma, A)$ versus A is accounted for by combining features of the VMD and parton models.)

Other comparisons utilizing VMD can be made

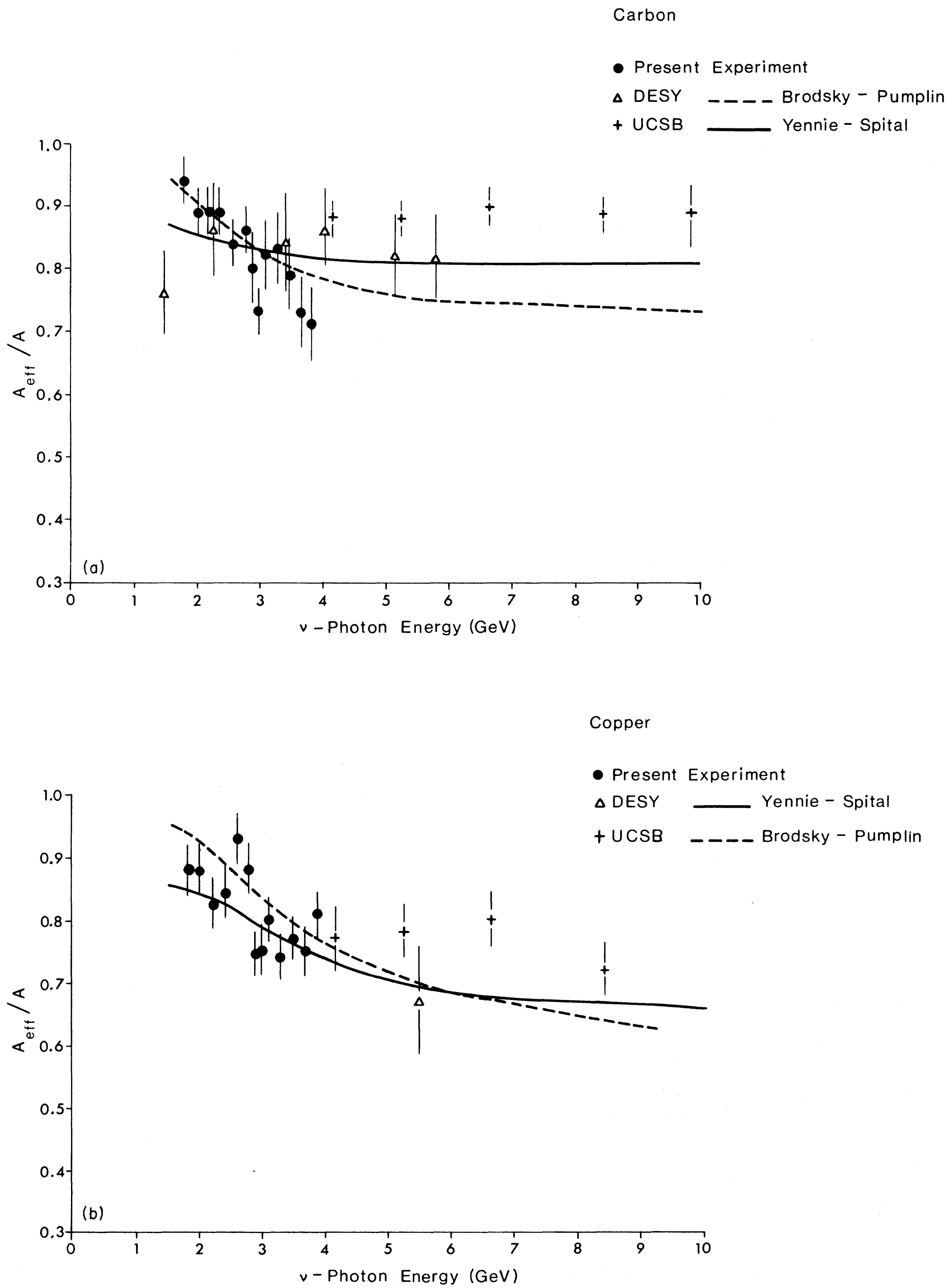

FIG. 3 *(Continued on following page)*.

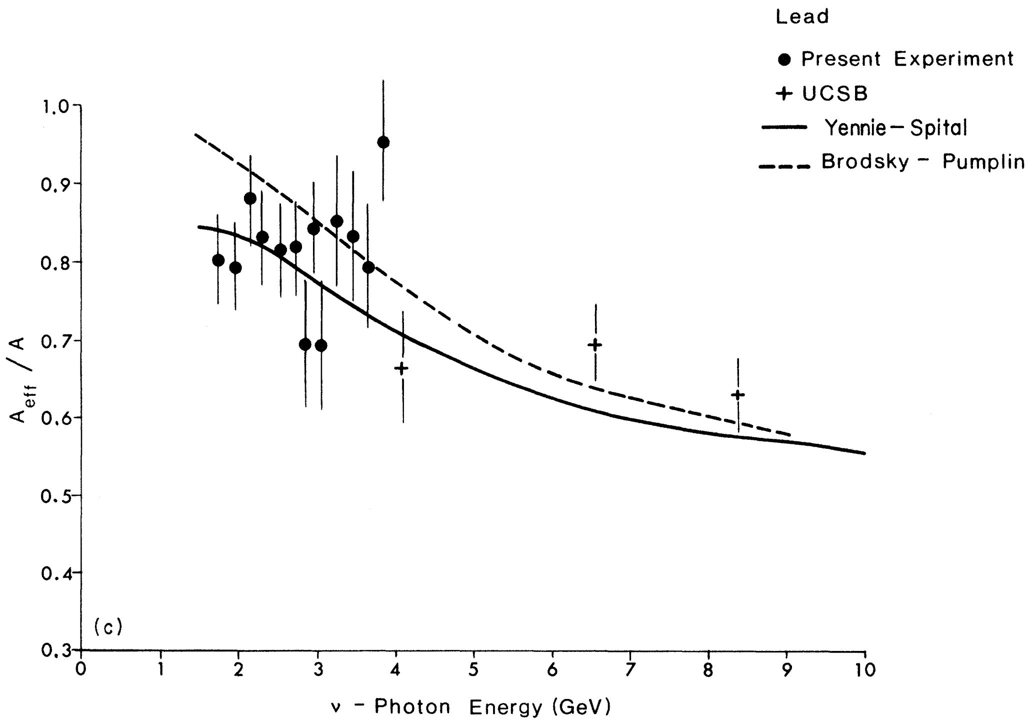

FIG. 3. Comparison of experiment with theory: A_{eff}/A versus ν, the laboratory energy of the photon in GeV, for carbon, copper and lead. Dashed line: after Brodsky and Pumplin.[11] Full line: after Gottfried and Yennie,[17] and Yennie and Spital (private communication). Data points with statistical errors: Δ Ref. 8, ● present experiment. Data points with statistical and systematic errors included: + Ref. 7.

on the basis of relations between total γ-ray cross sections and forward vector-meson photoproduction,[19] e.g.,

$$\sigma_T(\gamma p) = \sum_V \left[\frac{16\pi^2\alpha}{\gamma_V^2}\,\frac{1}{1+\eta_V^2}\,\frac{d\sigma}{dt}(\gamma p \to Vp)\bigg|_{t=0}\right]^{1/2}.$$

Here γ_V refers to the photon-meson coupling, and η_V to the ratio of real and imaginary parts of forward meson scattering (usually equated to those of γp scattering). A discussion of total cross-section data in this connection has been given recently by Gottfried,[20] and by Caldwell *et al.*[21] Such a comparison for the proton, with a value of $\gamma_\rho^2/4\pi$ of 0.64 ± 0.06 (see Ref. 22) indicates a short fall in the vector-meson contribution based only on ρ, ω, and ϕ mesons, which could be alleviated by the existence of higher-mass vector mesons. Some direct evidence in this direction has been recently accumulating.[23] The issues are also discussed by Sakurai and Schildknecht.[24]

In conclusion, the experimental results on $\sigma_T(\gamma A)$ reported here are hard to reconcile with extrapolations of the inelastic e-p scattering data[9] referred to earlier which, to date, show little shadowing at low q^2, but within error limits there is still room for some shadowing in that case.

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We are especially indebted to Professor D. R. Yennie for sending us a copy of a computer program which facilitated the calculations described in Sec. IV.

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APPENDIX: INPUT PARAMETERS FOR OPTICAL MODEL PROGRAM (ELSCAT)

Basic input parameters are the ρp, ωp, and ϕp total cross sections (where p denotes the proton), the meson's relative coupling strengths to the photon taken as $4\pi/\gamma_\rho^2 : 4\pi/\gamma_\omega^2 : 4\pi/\gamma_\phi^2 = 9:1:2$, and the ratio of the real (Ref) to imaginary (Imf) parts of the forward-scattering amplitude in γp scattering as a function of energy. It is assumed

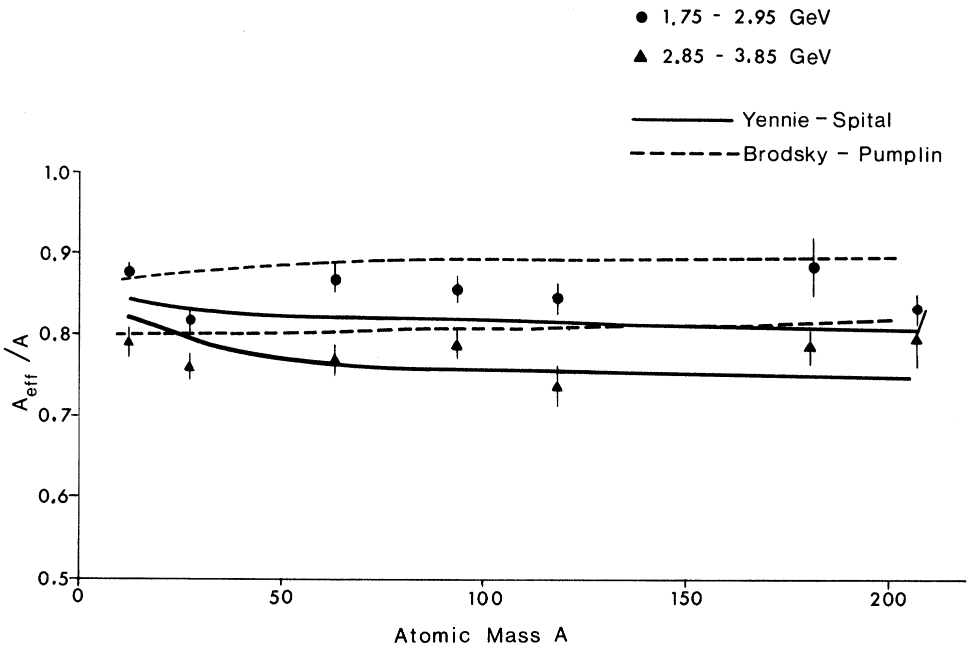

FIG. 4. A_{eff}/A versus A for the photon energy ranges 1.75 – 2.95 GeV and 2.85 – 3.85 GeV. Points are shown with statistical error bars. Full lines: Yennie and Spital (private communication). Dashed lines: after Brodsky and Pumplin.[11] The upper lines in each case refer to the energy range 1.75 – 2.95 GeV.

also that $\sigma_T(\rho p) \approx \sigma_T(\rho n)$.

From the quark-model relation

$$\sigma_T(\rho p) = \tfrac{1}{2}[\sigma_T(\pi^+ p) + \sigma_T(\pi^- p)] ,$$

the variation in $\sigma_T(\rho p)$ was taken in parametrized form, to fit the published data[25]:

$$\sigma_T(\rho p)_k = \sigma_T(\rho p)_\infty \left(1 + \frac{0.95}{k}\right) \text{ mb},$$

where k is the photon laboratory energy in GeV and $\sigma_T(\rho p)_\infty = 23.4$ mb.

Both $\sigma_T(\omega p)$ and $\sigma_T(\phi p)$ were kept fixed at 24 mb and 13 mb, respectively. The ratios $\text{Re}f/\text{Im}f$ were taken from previous work.[3,26] The sensitivity to a change in these ratios on the predictions for A_{eff}/A as a function of energy was investigated. For $\text{Re}f = 0$ at all energies, A_{eff}/A was decreased by only 3–4% for the heavier nuclei. Increasing the values of $\text{Re}f/\text{Im}f$ by 20% produced changes of approximately 1% in A_{eff}/A.

In the optical model, one of two nuclear-density distributions was used according as $A < 16$ or $A > 16$. In the former case (carbon), a shell-model type of density function[27] was tried:

$$\rho(r) = \rho_0\left[1 + \tfrac{4}{3}\left(\frac{r}{c}\right)^2\right]\exp\left(-\frac{r^2}{c^2}\right),$$

where $c = 1.65$ F. In the latter case (aluminum and heavier nuclei), the density function[28] was

$$\rho(r) = \rho_0\left[1 + \exp\left(\frac{r-c}{a}\right)\right]^{-1},$$

where $c = r_0 A^{1/3}$ is the half-density radius of the nucleus and a is the nuclear surface-thickness parameter. r_0 was taken as 1.12 F, and $a = 0.54$ F.

Account is also taken in this model for spatial correlation[29] of nucleon pairs within the nucleus and effects of charge smearing.

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