PHOTONUCLEON TOTAL CROSS SECTIONS AT VERY HIGH ENERGY*

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Photon-neutron total cross sections have been evaluated from the data for the proton and deuteron presented in the preceding paper. Simple Regge-pole fits have been made to $\sigma_T(\gamma p)$ and $\sigma_T(\gamma n)$, both of which extrapolate to 94 ± 4 μb at infinite energy. Over the range of our data, 3.7 to 17.9 GeV, $\sigma_T(\gamma n) < \sigma_T(\gamma p)$, which can be interpreted to give a ratio of exchange contributions, $A_2/P' = 0.19 \pm 0.04$. A fit to $\sigma_T(\gamma p)$ is also important for predictions of the proton cosmic-ray spectrum.

A comparison of total photoproduction cross sections for protons and neutrons provides a way to learn about the isospin-exchange nature of this basic process, which is related to Compton scattering by the optical theorem. A difference between $\sigma_T(\gamma p)$ and $\sigma_T(\gamma n)$ would be attributed to isovector exchange. Using the data of the preceding paper,[1] we obtain $\sigma_T(\gamma n)$ and make fits to this and to $\sigma_T(\gamma p)$, enabling the extrapolation of the cross sections to infinite energy. These fits, in a simple Regge-pole model, allow the assignment of specific amounts of P, P', and A_2 (isovector) exchange. The $\sigma_T(\gamma p)$ fit also can be used to predict the upper end of the proton cosmic-ray energy spectrum.

The neutron total photoabsorption cross sections were evaluated from the proton and deuteron data by the relation

$$\sigma_T(\gamma n) = \sigma_T(\gamma d) - \sigma_T(\gamma p) + \mathrm{GC}, \tag{1}$$

where GC is the Glauber correction for the shadowing of one nucleon by the other in deuterium. In a naive picture in which the photon interacts only electromagnetically, such shadowing would be negligible. However, in the ρ-like picture of the photon, which is substanitated by total cross section measurements on complex nuclei,[2] the photon acts like a hadron, resulting in significant shadowing. Following the formalism of Brodsky and Pumplin,[3] GC can be written as

$$\mathrm{GC} = I \frac{1-\eta^2}{1+\eta^2} \frac{d\sigma}{dt}(\gamma p \to \rho p)\big|_{t=0}, \tag{2}$$

where $d\sigma(\gamma p \to \rho p)/dt|_{t=0}$ is the differential ρ photoproduction cross section at zero four-momentum transfer, η is the ratio of the real to imaginary part of the $\gamma p \to \rho p$ amplitude, and I is an integral over momentum transfer of the product of the deuteron form factor and $d\sigma(\gamma p \to \rho p)/dt$. The value of I is relatively insensitive to the momentum transfer dependence of $d\sigma(\gamma p \to \rho p)/dt$, which was taken to be[3] $\exp(10t)$ for t in $(\mathrm{GeV}/c)^2$. Using as a deuteron form factor a fit to the Gartenhaus wave function,[4] and using $\eta = -0.2$,[5,6] we obtain[7] GC $= 4.5 \pm 0.9$ μb at 4 GeV and 4.0 ± 0.8 μb at 18 GeV.

The neutron cross section is then found from Eq. (1) with an error equal to the errors of the three terms combined in quadrature, since systematic errors common to the H and D data are small compared with the independent errors. The values for $\sigma_T(\gamma p)$ and $\sigma_T(\gamma n)$ averaged over each set of four tagging channels (at fixed incident positron energy) and their errors are shown in Fig. 1 and listed in Table I. The errors in the proton cross sections are typically 1.7% statistical and 1.0% systematic. Not included is an overall normalization error of 1.1%.

The similarity in the shapes of the photoabsorption cross sections (see Fig. 1) and strong-interaction total cross sections, such as those from pion-nucleon scattering, suggests a parametriza-

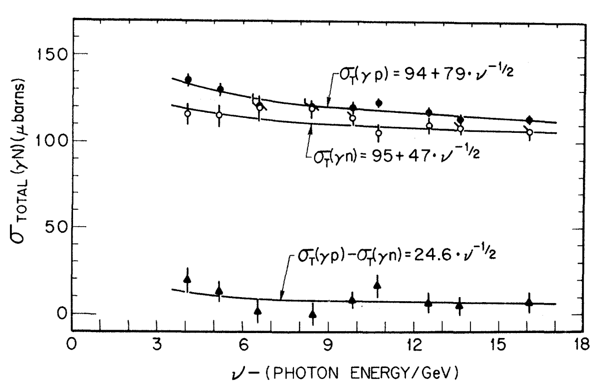

FIG. 1. Comparison of the proton, neutron, and proton-neutron difference data in Table I with ν fits of the form given in Eqs. (4) and (7).

Table I. Grouped data and errors for proton, deuteron, and neutron photoabsorption cross sections. The proton-neutron difference was calculated using the numerator of Eq. (7).

E_γ (GeV)	$\sigma_T(\gamma p)$ (μb)	$\sigma_T(\gamma d)$ (μb)	$\sigma_T(\gamma n)$ (μb)	$\sigma_T(\gamma p)-\sigma_T(\gamma n)$ (μb)
4.1	135.0±2.9	246.2±5.1	115.7±6.0	19.3±6.7
5.2	128.3±2.6	238.7±4.7	114.8±5.4	13.5±6.0
6.6	122.4±3.9	238.7±5.9	120.6±7.1	1.8±7.0
8.4	120.1±2.3	236.0±5.0	120.1±5.6	0.0±6.3
9.8	119.8±2.3	227.0±3.7	114.4±4.4	8.4±4.8
10.7	123.2±2.3	224.6±3.9	105.6±4.6	17.6±5.7
12.5	117.0±2.2	223.3±3.8	110.4±4.5	6.6±5.7
13.6	113.6±2.4	218.1±2.6	108.6±3.6	5.0±5.4
16.4	112.7±2.2	214.8±3.8	106.1±4.4	6.6±5.9

tion of our data similar to that frequently used in the latter cases.[8] Since the accuracy and extent of the photon data may not be sufficient to warrent the consideration of cuts, we have fitted to a sum of Regge-pole exchanges, which in the high-energy limit leads to

$$\sigma_T(s)=\sum_i c_i s^{\alpha_i(0)-1}, \tag{3}$$

where s is the square of the total energy in the center of mass per GeV,[9] c_i is a constant, and $\alpha_i(0)$ is the $t=0$ intercept of the angular momentum of the contributing trajectory. The leading trajectories with charge conjugation +1 and isospin 0 or 1 are the P [with $\alpha_p(0)$ defined to be unity] and the P' and A_2, both of which are observed to have $\alpha(0)\sim 0.5$ in fits[10] to hadron-hadron cross sections at high energies. Thus the data are fit by the simple form

$$\sigma_N(s)=a_N+b_N s^{-1/2}, \tag{4}$$

where N is the neutron or the proton. For some purposes it is more convenient to use ν, the incident photon energy in the laboratory per GeV,[9] in place of s. In either case this simple two-term form works quite well, since for either fit the χ^2 for 34 degrees of freedom is 33 for the proton and 37 for the neutron. This agreement, however, cannot be taken as strong evidence that the Regge-pole parametrization of the data is correct, since the results are insensitive to the power of s or ν which is used. Fits to the grouped (as in Table I) or ungrouped (Table I of Ref. 1) data give essentially the same values for the parameters (see Table II) and χ^2 confidence levels.

The neutron and proton data and their fits plotted in Fig. 2 against $\nu^{-1/2}$ indicate a neutron cross section which is less than that of the proton but tends to the same limit at infinity, $\sigma_N(\infty)=94.3\pm3.6$ μb (under the assumption of the $\nu^{-1/2}$ energy dependence).[11] To indicate the significance of the neutron-proton difference, the two fits shown have an acceptable 41% confidence level, obtained by adding their χ^2's and degrees of freedom. In contrast, a single fit in the form of Eq. (4), made on the assumption that the proton and neutron are identical, has a confidence level of only 0.3% and is clearly excluded. In addition, another fit, made on the assumption of an energy-independent proton-neutron difference, yielded an (8 ± 3)-μb difference with a confidence level of

Table II. Parameters in μb from ν fits to Eqs. (4), (6), and (7) using (a) data from this experiment only and (b) data of this experiment plus all data in Refs. 6, 14, and 15 with $\nu>2.0$.

ν fit parameters	a_p (μb)	b_p (μb)	a_n (μb)	b_n (μb)	c_{A_2} (μb)	$c_{P'}$ (μb)	$c_{A_2}/c_{P'}$
This experiment only	94.1±3.5	79.0±10.0	95.3±6.3	46.5±19.0	12.3±2.9	65.9±2.2	0.19±0.5
All data with $\nu>2.0$	99.0±2.5	61.8± 6.4	94.0±4.3	51.9±11.2	9.5±2.0	58.4±1.5	0.16±0.04

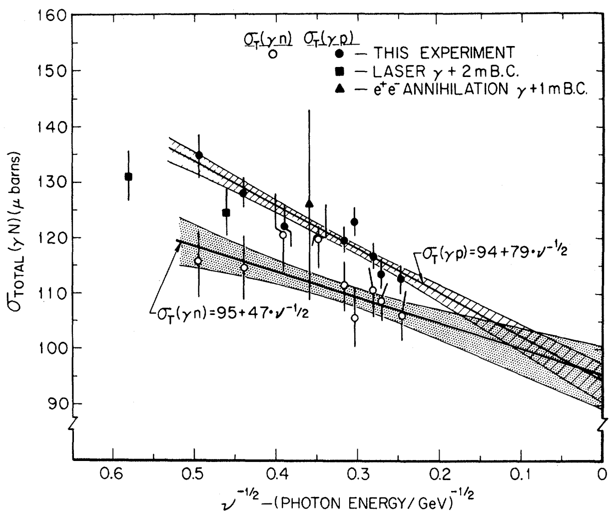

FIG. 2. Plot of neutron- and proton-grouped cross sections versus $\nu^{-1/2}$. Extrapolation to infinite energy values and uncorrelated errors of the best fits in the form of Eq. (4) are shown.

15%. We conclude that the neutron-proton difference is significant and that our data favor a difference decreasing with energy.

If one takes the simple Regge-pole exchange model seriously, then there are only three free parameters, since the Pomeranchuk (P) contributions a_n and a_p are both equal to $\sigma_N(\infty)$, a conclusion supported by our data. The relative contributions of the A_2 and P' can be determined from the energy-dependent terms in the fits. Since the P' is an isoscalar while the A_2 is an isovector, the A_2 contributes with opposite sign to the neutron and proton cross sections and produces the neutron-proton difference. Then we have

$$c_{P'} = [\sigma_p(s) + \sigma_n(s) - 2\sigma_p(\infty)]/2s^{-1/2}$$

and

$$c_{A_2} = [\sigma_p(s) - \sigma_n(s)]/2s^{-1/2} \tag{5}$$

for the P' and A_2 contributions, respectively. These can be expressed directly in terms of the measured proton and deuteron cross sections by the relations

$$c_{P'} = [\sigma_d(s) + \mathrm{GC} - 2a_p]/2s^{-1/2} \tag{6}$$

and

$$c_{A_2} = [2\sigma_p(s) - \sigma_d(s) - \mathrm{GC}]/2s^{-1/2}. \tag{7}$$

The numerator of Eq. (7) gives the best method for evaluating the proton-neutron differences, since some systematic errors common to the proton and deuteron measurements are reduced. These differences are displayed in Fig. 1 and are given in Table I, while the values of $c_{P'}$ and c_{A_2} obtained from fits to Eqs. (6) and (7) are given in Table II. The result is that the ratio of A_2 and P' contributions to the energy dependence of the cross sections is $A_2/P' = 0.19 \pm 0.04$,[12] which is another way to express quantitatively that $\sigma_p(s) \neq \sigma_n(s)$. It is interesting to note that Harari, in a calculation of the neutron-proton mass difference,[13] predicted an A_2 contribution which gives a $\sigma_p - \sigma_n$ energy dependence such as we observe.

All of the results given above are based on the data from this experiment. In Fig. 2 other published data[14,15] on photon-proton cross sections are shown for comparison. In addition, important preliminary results from a Stanford Linear Accelerator Center spectrometer group[16] and, at lower energies, from a DESY counter group[6] have been reported at the Liverpool conference. Where there is energy overlap, all of the measurements appear to be in agreement within the stated errors. Since the parameters are sensitive to the low-energy data, we have made additional fits which include the preliminary result of Ref. 6 and the other published cross sections,[14,15] using only measurements with incident photon energy greater than 2.0 GeV, to avoid the resonance region. As shown in Table II, inclusion of the additional data does not appreciably change the A_2/P' ratio. The χ^2 per degree of freedom is about 1.1 for all the fits.

The results of this experiment, as well as others known at the time of the Liverpool conference, have been used by Damashek and Gilman[5] to test dispersion relations for Compton scattering. Two of their results are pertinent here. First, if the Regge-pole analysis of the total cross-section data is taken seriously—i.e., if the form of Eq. (4) is correct (and recall that it is consistent with, but not forced by, the data) —then the dispersion relations seem to require an extra real constant, in addition to that which the energy dependence of $\sigma_T(\gamma p)$ and Regge theory would predict. This constant is consistent with the Thomson limit, which could correspond to a fixed pole of $J=0$.[17] Second, the dispersion relations show that the Compton amplitude has an appreciable real part, which is about -0.2 of the imaginary part in our energy range. An important implication of this result is that if the vector-dominance model is correct, then the ρ photoproduction amplitude should also have the same ratio of real to imaginary parts; hence, $\eta = -0.2$

in Eq. (1).

Finally, we note that the intensity and shape of the high-energy proton cosmic-ray spectrum reflects the magnitude and energy dependence of $\sigma_T(\gamma p)$. Because the photons from the 2.7°K blackbody radiation, presumably remaining from the initial stages of the expansion of the universe, can collide with very high-energy protons to produce other hadrons, the lifetime of such protons in the universe is shortened. Since the cross section we find is about twice that used in recent calculations of this effect,[18] the very high-energy proton cosmic-ray fluxes should be less than has been predicted.

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[7]We have assigned a 20% error to GC which includes theoretical uncertainties, as well as two effects which tend to cancel: the neglect of the difference between $d\sigma(\gamma p \to \rho p)/dt|_{t=0}$ and $d\sigma(\gamma n \to \rho n)/dt|_{t=0}$ and the neglect of diffractive ω and φ production.

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[10]See, for example, the review by V. Barger, in *Proceedings of the Topical Conference on High Energy Collisions of Hadrons, CERN, January 1968* (CERN Scientific Information Service, Geneva, Switzerland, 1968), Vol. 1, p. 3.

[11]Fits using $s^{-1/2}$ yield $\sigma_N(\infty) = 93.0 \pm 3.8\ \mu$b. The recent Serpukhov hadron-hadron total-cross-section measurements indicate that such extrapolations, however, should be treated with caution (see Ref. 10). Nevertheless, it is interesting that A. H. Mueller and T. L. Trueman, Phys. Rev. 160, 1306 (1967) predicted $\sigma_N(\infty) = 95\ \mu$b if the P contribution has a singular residue rather than there being a $J=1$ pole at $t=0$.

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