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Forward Compton Scattering from Hydrogen and Deuterium at 8 and 16 GeV*

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Compton-scattering cross sections from hydrogen ($\gamma p \to \gamma p$) and from deuterium have been measured at four-momentum transfer t in the range $0.014 \leq -t \leq 0.17$ GeV^2 and photon energies of 8 and 16 GeV. Fits to our proton data of the form $d\sigma/dt = Ae^{Bt}$ give $B \approx 7.8$ GeV^{-2} and an intercept A which is in agreement with the optical point. Both coherent scattering from deuterons and incoherent scattering from neutrons and protons are seen from deuterium. A small difference between the neutron and proton cross sections is seen, indicating the presence of about a 3% isovector t-channel exchange amplitude in addition to the predominant isoscalar amplitude. The vector-dominance model predicts lower cross sections (by at least 20%) for both the hydrogen and deuterium cases.

Elastic scattering of photons (Compton scattering) by nucleons is a fundamental process. The forward differential cross section is related to the total cross section by the optical theorem and by dispersion relations.[1] At high energies, comparison of Compton scattering and photoproduction of vector mesons (ρ, ω, φ) provides one of the more direct tests of the vector-dominance model (VDM). Data[2-4] exist for Compton scattering from protons with four-momentum transfer $-t \gtrsim 0.06$ GeV^2. We report here new measurements at smaller $-t$ (0.014 to 0.17 GeV^2) for proton Compton scattering. We also present data for Compton scattering from deuterons, which has not been previously measured at high energies. The latter process provides new tests of the optical theorem and the VDM and, through comparison with the γp data, provides a measure of the isovector exchange amplitude.

The data were taken at the Stanford Linear Accelerator Center by bombarding a 15-in. liquid-hydrogen or liquid-deuterium target with a bremsstrahlung beam (0.0285 radiation length radiator) and measuring the angle and energy of scattered photons with a pair spectrometer positioned 40 m from the target. Charged particles from the target were eliminated by a sweep magnet positioned 24 m from the target along the beam line to the pair spectrometer. The pair spectrometer had a converter (0.044 radiation length of copper, 10 cm wide × 13 cm high) in front of a magnet with a 6-in. gap 72 in. long, which was oriented to bend the pair-produced electrons and positrons in the vertical plane as shown in Fig. 1. Scintillation-counter hodoscopes

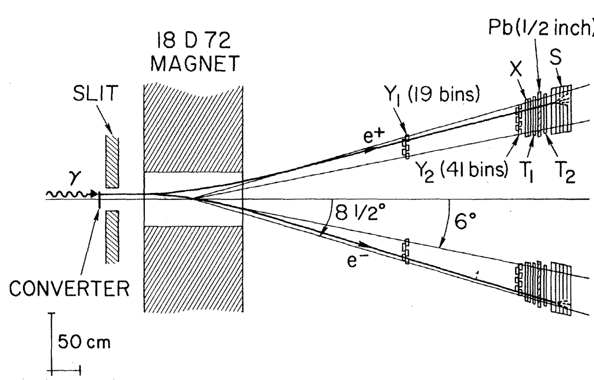

FIG. 1. Schematic of the pair spectrometer in the vertical plane.

Y_1 and Y_2 in each arm defined the bend angles for the e^+ and e^- particles and their approximate vertical source positions at the converter, while hososcopes X (15 bins) oriented perpendicular to Y_2 provided the horizontal source positions. Each arm had a full momentum acceptance $\Delta p/p$ of 34%. Chance pairs from two different photons, or pairs originating in the helium gas within the magnet were eliminated by requiring the e^+ and e^- to have similar source positions at the converter. Triggering in each arm was done by scintillation counters T_1 and T_2 and a 14-radiation-length lead-Lucite-sandwich shower counter S. The event trigger was $(T_1T_2S)_{+\mathrm{arm}}(T_1T_2S)_{-\mathrm{arm}}$. Background rates were reduced by surrounding the counters with at least 3 ft of concrete and by shielding the magnet pole faces by slits located in front of the converter and the sweep magnet.

The efficiency for detection of a photon of energy k by the spectrometer is a maximum, of approximately 0.14 times the thickness of the converter in radiation lengths, at the central spectrometer energy E_{sp} and falls to 0 at energies ±17% away from E_{sp}. The calculated rms energy resolution of the pair spectrometer was ±0.7%. The calculated efficiency and resolution were checked by measuring the tip of the bremsstrahlung spectrum at 0°, which gave the expected resolution, but a (4±2)% lower efficiency than calculated.

The bremsstrahlung beam was monitored as in previous photoproduction experiments[5] by a secondary-emission quantameter (SEQ) positioned 13 m behind the target and by a gas Cherenkov monitor and an ion chamber in front of the target. The detection counters were shielded from muons produced at the SEQ beam stopper by 8 m of iron placed between the SEQ and the sweep magnet. For the 0° bremsstrahlung measurements at very low beam currents, an ionization quantameter[6] was used behind the pair spectrometer.

Data were taken at various angles from hydrogen and deuterium with the converter in and out (out/in rate = 0.15 ± 0.01). The empty target rate was typically 5% of the hydrogen rate at the larger angles, and as high as 30% at the smallest angle. Other corrections included trigger deadtime (<5%), hodoscope deadtime (<2%), multitrack events which were not decoded (<13%), γ absorption in the target, helium bags, windows, and air (8%), and the normalization as measured from the 0° bremsstrahlung spectrum (4%). After including the spectrometer efficiency, spectra

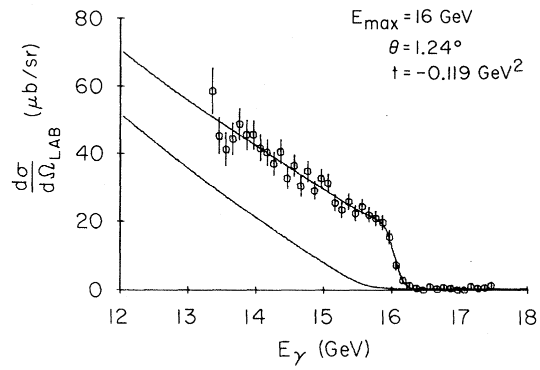

FIG. 2. A typical energy spectrum of scattered photons having energies near the end point of the bremsstrahlung beam. The bottom line is the sum of linear background terms; the upper line includes the Compton step also.

were obtained for each datum point, one of which is shown in Fig. 2.

The processes assumed in fitting the data were (1) a Compton step, variable in height; (2) a fixed linear term beginning at the bremsstrahlung end-point energy computed from the processes $\gamma N \to \pi^0 N$ [7,8] with $\pi^0 \to \gamma\gamma$ and $\gamma N \to \eta N$ [7] with $\eta \to \gamma\gamma$; (3) a fixed linear term starting at the final γ threshold for the process[9] $\gamma N \to \omega N$ with $\omega \to \gamma\pi^0$; (4) a variable linear term starting at the final γ threshold for $\gamma N \to \pi^0\Delta(1238)$ with $\pi^0 \to \gamma\gamma$; and (5) a variable flat-background term describing chance triggers. The end-point energy was allowed to vary to account for any spectrometer energy miscalibration. These processes were folded with the bremsstrahlung spectrum, the e^+ and e^- straggling in the converter, and the spectrometer resolution. Inclusion of an additional variable quadratic term to account for other inelastic processes made little change in the Compton answers. Allowing a 25% uncertainty in process (2) results in only a 3% (1%) change in the Compton answer at 8 (16) GeV. The Compton answers are even less sensitive to variation in processes (3) and (4). A systematic error estimated at 3% (2%) for the 8 (16) GeV fits has been added in quadrature to the statistical errors. An overall systematic error of ±3% common to all points has not been included. The results are shown in Fig. 3 and Table I.

The proton data show the distribution $d\sigma/dt = Ae^{Bt}$ as expected from a diffraction process. Using only our data, we obtain fit (a) tabulated below. For the combined data of this experiment and those of Ref. 2 ($0.10 \leq -t \leq 1.0$ at 8.5 and 17

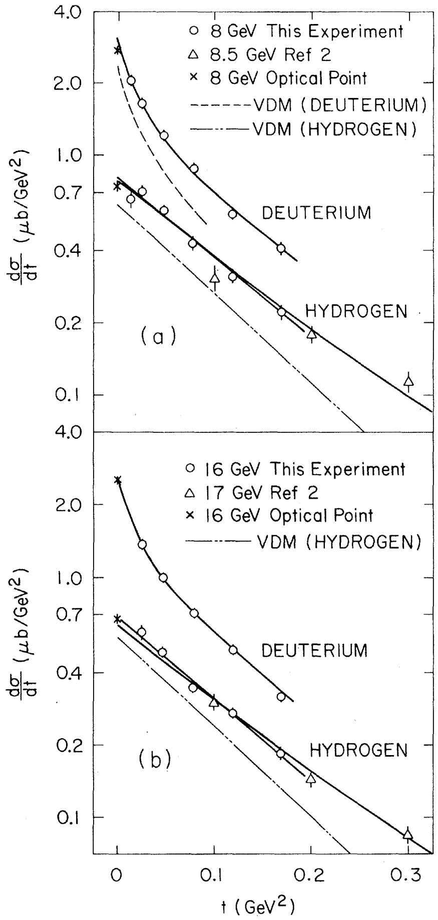

FIG. 3. Cross sections $d\sigma/dt$ (μb/GeV^2) for $\gamma p \to \gamma p$ and the deuterium process $\gamma D \to \gamma D$ (γpn) at 8 and 16 GeV. The solid lines for hydrogen are the fits Ae^{Bt} (these data) and Ae^{Bt+Ct^2} (these data + those of Ref. 2); for deuterium the line is Eq. (1), using the proton t dependence Ae^{Bt} and the fitted parameters of Eq. (2).

GeV), fits of the form Ae^{Bt+Ct^2} give fit (b).

E (GeV)	Fit	A (μb/GeV^2)	B (GeV^{-2})	C (GeV^{-4})
8	(a)	0.82 ± 0.04	7.7 ± 0.5	•••
	(b)	0.79 ± 0.03	7.6 ± 0.4	2.3 ± 0.5
16	(a)	0.69 ± 0.03	7.9 ± 0.5	•••
	(b)	0.64 ± 0.02	7.3 ± 0.3	1.7 ± 0.3

The forward cross section for the elastic scattering process $\gamma p \to \gamma p$ is given by[1]

$$\frac{d\sigma}{dt}(k)\bigg|_{t=0} = \frac{1}{16\pi}\left|\sigma_{\rm tot}(k)\right|^2 + \frac{\pi}{k^2}\left|{\rm Re}[f_1(k)]\right|^2 + \frac{\pi}{k^2}\left|f_2(k)\right|^2,$$

Table I. Cross sections $d\sigma/dt$ (μb/GeV^2) for $\gamma p \to \gamma p$ and γD $\to \gamma$D (γpn).

E	t	$(d\sigma/dt)_p$	$(d\sigma/dt)_{\rm D}$
8	0.014	0.66 ± 0.05	2.05 ± 0.09
	0.025	0.71 ± 0.04	1.66 ± 0.07
	0.047	0.59 ± 0.03	1.21 ± 0.06
	0.078	0.43 ± 0.03	0.88 ± 0.04
	0.119	0.315 ± 0.020	0.575 ± 0.033
	0.169	0.223 ± 0.015	0.410 ± 0.021
16	0.025	0.59 ± 0.04	1.37 ± 0.06
	0.047	0.489 ± 0.021	0.996 ± 0.032
	0.078	0.348 ± 0.015	0.710 ± 0.025
	0.119	0.271 ± 0.013	0.503 ± 0.020
	0.169	0.185 ± 0.011	0.321 ± 0.014

where f_1 (f_2) is the amplitude for parallel (perpendicular) polarization vectors in the initial and final photons. The optical theorem [${\rm Im}f_1 = (k/4\pi)\sigma_{\rm tot}$] has been used in the above relation. Damashek and Gilman have made estimates for ${\rm Re}f_1(k)$ from dispersion relations, which contribute approximately 4% (2%) to $d\sigma/dt|_{t=0}$ at 8 (16) GeV. Using the total cross sections of Caldwell *et al.*,[10] the comparison of $d\sigma/dt|_{t=0}$ with the optical theorem and the dispersion calculations, neglecting f_2, is shown in Fig. 4. Our data give approximately a 10% upper limit for the f_2 term (two standard deviations).

In the case of deuterium, the data show a sharp forward peak from the coherent deuterium scattering with an incoherent part which remains at larger t. The deuterium cross section, ignoring

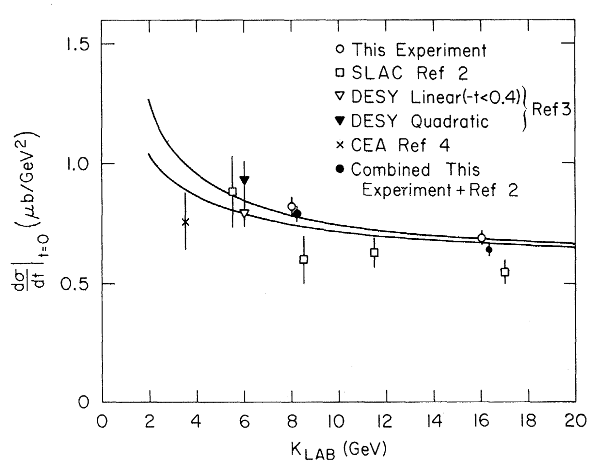

FIG. 4. Energy dependence of $d\sigma/dt|_{t=0}$ for $\gamma p \to \gamma p$. The lower curve is the optical point only, while the upper curve includes the real part as estimated in Ref. 1.

spin effects, is given by[11,12]

$$(d\sigma/d\Omega)_D = 2|a_0|^2[1+F(t)+2G(t)] + 2|a_1|^2[1-F(t)], \quad (1)$$

where a_0 and a_1 are the respective isoscalar and isovector t-channel exchange amplitudes off nucleons, $F(t)$ is the deuterium form factor, and $G(t)$ is the Glauber scattering term. For hydrogen, $(d\sigma/d\Omega)_H = |a_0+a_1|^2$. We have used $F(t)=e^{56t}$ at small t obtained from electron scattering,[13] and $G(t) = -0.069e^{-Bt/4} + 0.007e^{-Bt/2}$ from the calculations of Ogren,[11] with $B=7.8$ GeV^2.

The ratio of deuterium to hydrogen can be expressed by two unknown parameters; and from the combined 8- and 16-GeV data, fits to the D_2/H_2 ratios versus t give, for these parameters,

$$\mathrm{Re}(a_0{}^*a_1)/|a_0+a_1|^2 = 0.030 \pm 0.015, \quad (2a)$$

and

$$|a_1|^2/|a_0+a_1|^2 = -0.09 \pm 0.11. \quad (2b)$$

If we assume, with no justification, that a_0 and a_1 have the same t dependence and the same phase, then we get $a_1/a_0 \approx 0.030 \pm 0.015$. This is consistent with the value derived by the optical theorem from total γp and γn cross-section measurements, namely,

$$\frac{a_1}{a_0} \approx \frac{\mathrm{Im}a_1}{\mathrm{Im}a_0} = \frac{\sigma_T(\gamma p)-\sigma_T(\gamma n)}{\sigma_T(\gamma p)+\sigma_T(\gamma n)} = \begin{cases} 0.039 \text{ at 8 GeV}, \\ 0.027 \text{ at 16 GeV}. \end{cases}$$

Comparison of Compton scattering with the production of the vector mesons $\rho^0\omega$ and φ, provides one of the most direct tests of VDM, which predicts for γp scattering,

$$\frac{d\sigma(\gamma p \to \gamma p)}{dt} \leqslant \left[\sum_{V=\rho,\,\omega,\,\varphi} g_{V\gamma}{}^2 \left(\frac{d\sigma(\gamma p \to V^{\mathrm{tr}} p)}{dt} \right)^{1/2} \right]^2.$$

Using the coupling constants $g_{V\gamma}{}^2$ from the Orsay storage rings,[14] and the measured ρ,[7] ω,[9] and φ[7] cross sections[15] for the transverse vector-meson cross sections, the VDM prediction is shown in Figs. 3(a) and 3(b) for maximum constructive interference between the vector amplitudes. At lower energies, different methods of analysis have given ρ^0 cross sections with flatter t distributions, but smaller values near $t=0$ (see Ref. 3). We can conclude that the VDM prediction is at least 20% below our γp cross sections. Using the measured ρ cross section from deuterium at 7.5 GeV[15] and 9 GeV,[16] and assuming that ω and φ production are equal from neutrons and protons, a VDM prediction can also be made for deuterium at 8 GeV. The VDM discrepancy for the deuterium case is similar to the hydrogen case, as shown in Fig. 3(a).

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