Elastic Photon-Proton Scattering in the 50–130-GeV Range

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In the tagged-photon beam at Fermilab, differential cross sections were measured for the elastic scattering of photons on a liquid-hydrogen target. The diffractive forward peak was measured for photon energies between 50 and 130 GeV and $|t|$ values between 0.07 and 1.20 $(GeV/c)^2$. The shape of the diffraction peak is similar to that seen in π-p scattering. The magnitude is that predicted by the optical theorem.

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We have performed a photoproduction experiment looking at forward final states characterized by electromagnetically showering particles. Here we report a measurement of the differential cross section for elastic photon-proton scattering. Traditionally this reaction has been used to study the interplay of vector-meson scattering and photon scattering as postulated by the vector-meson dominance model.[1] Our experiment extends the energy range for this measurement beyond the previous value of 18-GeV photon energy.[2]

We measured this reaction in the Fermilab tagged-photon laboratory.[3] Typically 10^{13} 400-GeV/c protons were accelerated each pulse, giving a 1-sec spill of 3×10^{12} protons onto a beryllium target in the "proton east" line. After conversion of forward neutrals in 0.57 radiation lengths of lead, 7×10^6 135-GeV/c electrons with $\Delta p/p = \pm 2.2\%$ were transported to a 5.5%-radiation-length copper radiator. Magnets dispersed the resulting beam such that those electrons which had between 5% and 60% of the beam energy crossed a bank of overlapping scintillator hodoscopes and were absorbed in an array of shower counters. This system tagged approximately 2×10^5 incident photons per beam spill. At the target, the photon beam was ±7 mm wide and ±4 mm high, with divergences of ±0.6 mrad and ±0.16 mrad, respectively. The target was a 3-cm-diam by 75-cm-long vessel of condensed liquid hydrogen inside a concentric 7.9-cm-diam cylindrical wall of 0.250-mm-thick Mylar. We detected the final state of this reaction with a recoil spectrometer and a forward electromagnetic calorimeter.

The angle of the scattered proton was measured by recoil drift chambers arranged in four quadrants around the target. Each quadrant consisted of two modules of four drift-chamber planes each. We chose pure ethylene gas,[4] C_2H_4, since its

velocity saturates near our operating voltage of −1.2 kV/cm. The drift field was provided by uniformly graded electrostatic-potential cathode wires, 120-μm-diam Be copper, spaced every 2 mm.[5] Each cell had an intercathode gap of 7.5 mm, one 20-μm tungsten sense wire, and a maximum drift length of 4 cm. Each module consisted of four planes of sense wires with the following orientations with respect to the beam: normal, parallel, normal + 18°, and normal − 18°. The inner (outer) modules had sensitive areas of 48 ×80 cm² (96 ×96 cm²) and were placed at 30 cm (55 cm) from the beam line to form a square. The module frames shadowed 24% of the azimuthal angles.

A barrel of sixteen 40 ×150 ×1.27-cm³ scintillation counters with photomultipliers on both ends also surrounded the target at a distance of 1 m. They provided an azimuthal-angle hodoscope, registering the presence of a recoil particle in the event.

A number of scintillation counters were used to detect charged particles going forward in the center of mass of the reaction: The principal set, 20 m from the target, was a band of six counters which shadowed our forward shower detector. These counters, introduced after half of our data had been taken, allowed us to measure the contamination of our signal by background reactions resembling elastic scattering in all aspects except that the forward showering particle was charged.

Our forward electromagnetic calorimeter[6] was located 28 m downstream of the target. It was composed of sixteen pairs of lead-Plexiglas sampling total-absorption counters. Each counter was 18 cm high by 72 cm wide. The sixteen upstream counters were preceded by 2.2 radiation lengths of lead. Each one consisted of seven layers of 1.27-cm-thick Plexiglas sheets interspersed with 1.1-radiation-length (0.64-cm) lead

sheets. The sixteen downstream counters had ten similar layers behind a 0.64-cm sheet of lead. The Cherenkov light from each counter was guided onto a 5-in-diam photomultiplier tube, placed on the end away from the beam. The longitudinal segmentation permitted us to reject most hadron-initiated showers, since they typically deposited less than 10% of their total energy in the upstream element. Each bank of sixteen counters was arranged to form an 8×8-cm^2 hole for the beam. Two fine-grained scintillator hodoscopes were installed between the two banks of the sampling total-absorption counter. They measured the vertical and horizontal profiles of the shower giving a position determination of better than 3 mm. Each hodoscope consisted of 48 3-cm-wide $\times 2.5$-cm-thick $\times 158$-cm-long scintillator strips, while two opposing sets of four 2-cm-wide $\times 92$-cm-long strips allowed for a beam hole.

Our trigger was a coincidence between the photon-tagging system and a signal coming from our forward detector. The forward-detector pulse was required to exceed an energy deposition of at least 35 GeV, with at least 1.75 GeV in the upstream absorption counters.

We selected elastic events from our data of 2.3×10^6 triggers by requiring (1) consistency between the trajectory and energy measurements for the tagging electrons; (2) reconstruction of a single shower with energy at least 80% of the nominal tagged-photon energy; (3) the shower position in the forward calorimeter at least 3.5 cm from the beam hole edge; (4) a successfully reconstructed track (hits on at least seven of the eight planes were required) in the drift-chamber quadrant opposite the forward shower; (5) extrapolation of the recoil track passing within 1 cm of the target; and (6) a probability greater than 1.5% for a fit to an elastic scatter of a photon of energy predicted by the tagging system. (The fit was made to the event's transverse momentum and tangent of the azimuthal angle measured by the recoil drift chambers and the forward hodoscope.) A total of 1908 events successfully passed the above requirements.

We determined our efficiencies using Monte Carlo simulation techniques which included the effects of multiple radiation[7] and geometrical inefficiencies. We had a total flux of 1.2×10^{10} tagged photons after removing events with inconsistent tagging information and after a 4.3% correction for absorption of photons by the target.

Several corrections to the number of events

were necessary: (1) The charged-particle bank rejected background processes (predominantly $\gamma \rightarrow e^+ e^-$ followed by ep elastic scattering) which satisfied all our criteria, except that the forward showering particle was charged. Figure 1(a) shows the distribution in the difference between the measured and the expected forward energy normalized to the expected energy irrespective of information from the charged-particle bank. Figure 1(b) shows the same distribution, after requiring that this bank have no signal. We used the latter data to correct for these background processes in our distributions from the whole data sample. (2) We applied a 3% correction for the reaction $\gamma p \rightarrow \omega p$, with $\omega \rightarrow \pi^0 \gamma$. (3) We corrected for two sources of track reconstruction
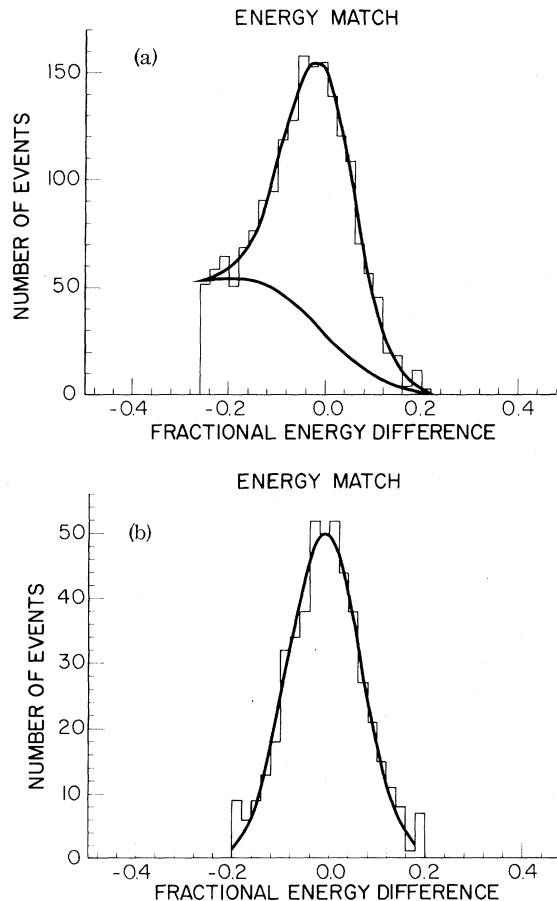

FIG. 1. (a) Histogram of the difference between the measured and predicted forward energy plotted as a fraction of the predicted forward energy disregarding the charged-particle bank. Superimposed is the Gaussian fit of (b) plus background. (b) Same distribution as in (a) requiring no particle in charged-particle bank. Superimposed is an unconstrained Gaussian fit.

TABLE I. Differential cross sections.

Energy Range (GeV)	$\lvert t \rvert$ (GeV/c)^2	# Events	$d\sigma/dt$ (nb(GeV/c)$^{-2}$)		Single Exponential Fit (I)	
					A nb(GeV/c)$^{-2}$	b (GeV/c)$^{-2}$
50 – 75	.07 – 0.10	150	328	± 64	622 ± 85	7.7 ± .5
	.10 – 0.15	157	214	± 36		
	.15 – 0.24	146	146	± 21		
	.24 – 0.40	103	63.5	± 9.7		
	.40 – 0.70	41	15.2	± 3.6		
	.70 – 1.20	7	0.62	± 0.5		
75 – 95	.07 – 0.10	114	284	± 72	487 ± 86	6.6 ± .6
	.10 – 0.15	127	213	± 44		
	.15 – 0.24	105	150	± 26		
	.24 – 0.40	84	57.6	± 11		
	.40 – 0.70	44	24.5	± 5.9		
	.70 – 1.20	7	1.61	± 1.3		
95 – 130	.10 – 0.15	126	234	± 46	546 ± 117	7.2 ± .7
	.15 – 0.24	136	145	± 24		
	.24 – 0.40	92	54.2	± 11		
	.40 – 0.70	48	15.3	± 3.7		
	.70 – 1.20	11	2.77	± 1.8		
Total	.07 – 0.10	308	360	± 54	541 ± 53	6.9 ± .3
	.10 – 0.12	201	236	± 43		
	.12 – 0.15	209	202	± 30		
	.15 – 0.19	210	178	± 24		
	.19 – 0.24	177	123	± 17		
	.24 – 0.30	135	73.8	± 12		
	.30 – 0.40	144	49.4	± 7.4		
	.40 – 0.50	79	28.2	± 5.7		
	.50 – 0.70	54	12.0	± 2.4		
	.70 – 1.20	25	1.50	± .65		

losses: nuclear scatters (3% of our recoil tracks) and excessive random drift-chamber hits (11%).

Several other potential backgrounds had upper limits which did not warrant correction: random signals (negligible), target-empty rate (2 ± 2 nb), the reaction $\gamma p \to \pi^0 p$ ($\leq 5\%$ of the events at our lowest beam energy), and the reaction $\gamma p \to \gamma N^*$ (we have roughly 2% acceptance for the N^* events fitted to the elastic hypothesis).

Table I gives our results for the differential cross section, both for three intervals of photon beam energy and averaged over all beam energies. The following functional forms give equally good fits to our data: (I) $d\sigma/dt = A e^{bt}$ or (II) $A\exp(8.9t + 2.2t^2)$. The latter corresponds to the shape of the sum of the $\pi^+ p$ and $\pi^- p$ elastic cross sections.[8]

Figure 2(a) shows our differential cross-section values for the three beam-energy intervals with a curve given by fit of form I to our data averaged over all beam energies. We find the slope parameter to be constant within 10% over our energy range of 50–130 GeV, consistent with hadronic scattering data.

Figure 2(b) shows the beam-energy–averaged differential cross sections with the curve from II normalized to our data. The lower bound on the differential cross section from the optical theorem, using the measured γp total cross section at our average energy,[9] is 681 ± 12 nb/(GeV/$c)^2$, shown at $t = 0$, where I and II give 541 ± 53 nb/ (GeV/$c)^2$ and 726 ± 38 nb/(GeV/$c)^2$, respectively. Fit II, which is preferred theoretically, is more compatible with the optical lower bound. Both fits are consistent with a forward amplitude which is predominantly imaginary.
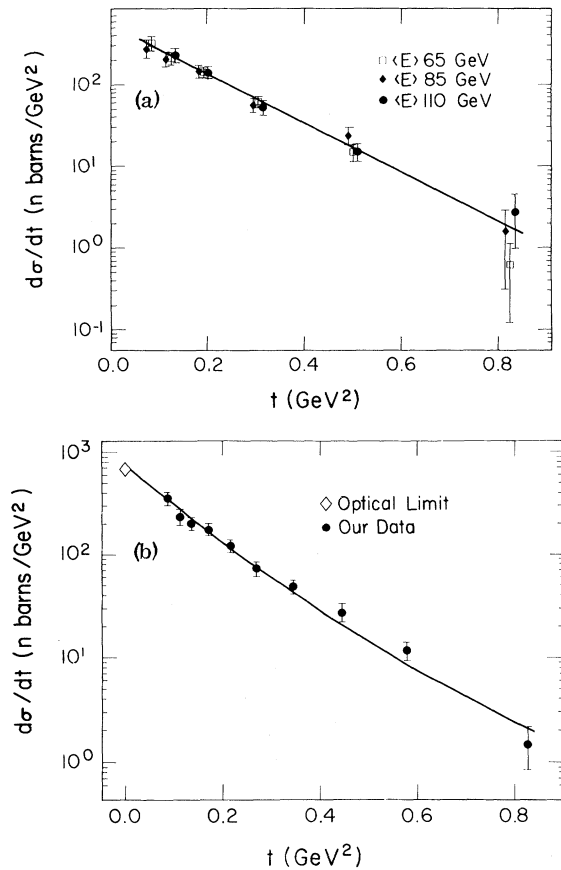
FIG. 2. (a) Differential cross sections for three beam energies with curve from fit I. (b) Differential cross sections for all energies with curve from fit II.

Summing our beam-energy-averaged data [for $|t| \geqslant 0.07$ $(GeV/c)^2$] with our fit by II [for $|t| < 0.07$ $(GeV/c)^2$] gives 88 ± 4 nb for the elastic γp cross section, roughly 0.075% of the total photon cross section.

The vector-meson dominance model[1] predicts a maximum value for the elastic γp cross section:

$$\frac{d\sigma}{dt}(\gamma p \to \gamma p) = \frac{\alpha}{4}\left\{\sum_v\left[\frac{4\pi}{\gamma_v^2}\frac{d\sigma}{dt}(\gamma p \to vp)\right]^{1/2}\right\}^2,$$

corresponding to maximum interference. If one evaluates this sum with only ρ, ω, φ, and ψ con-

tributions, the φ contributes about 10% and the ψ negligibly at $t = 0$. The light u and d quark states are expected to dominate, motivating the use of $\pi^\pm p$ data alone for fit II. We note, however, that as observed at lower energies,[2] the absolute value of the cross section at $t = 0$ is about twice the value obtained by using the vector-meson dominance model[1] with only the ρ, ω, and φ vector mesons.

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