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Small-Angle Compton Scattering on Hydrogen and Deuterium

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Abstract

We have measured elastic scattering of 5 and 6 GeV photons on hydrogen and deuterium in the angular range 10-50 mrad. On hydrogen we observe a forward diffraction peak with a slope of 8.5 (GeV/c)^{-2} . The extrapolated forward cross sections in units $\mu\text{b}/(\text{GeV/c})^2$ are $.82 \pm .04$ at 5 GeV and $.79 \pm .04$ at 6 GeV. They are consistent with the calculated amplitudes obtained from total cross section measurements via the Optical Theorem and dispersion relations assuming negligible contributions of spin-dependent amplitudes. Deuterium cross sections show a transition from coherent scattering at low $|t|$ to incoherent scattering at higher $|t|$. They indicate that the isovector exchange amplitude a_1 is very small compared to the isoscalar a_0 .

We obtain

$$|a_1|^2 / |a_0 + a_1|^2 = 0.13 \pm 0.09$$

$$\text{Re}(a_0 a_1^*) / |a_0 + a_1|^2 = 0.0 \pm 0.03 \quad \text{at 5 GeV}$$

and

$$|a_1|^2 / |a_0 + a_1|^2 = -0.12 \pm 0.15$$

$$\text{Re}(a_0 a_1^*) / |a_0 + a_1|^2 = 0.10 \pm 0.04 \quad \text{at 6 GeV}$$

Many conclusions drawn from elastic photon-nucleon scattering depend on a precise knowledge of the forward cross section. Photon detectors trying to approach the forward direction, however, have to cope with an increasing background caused by Q.E.D. reactions.

We have measured Compton scattering on hydrogen at 6 GeV, and in a second, slightly modified experiment on hydrogen and deuterium at 5 GeV, both at particularly small momentum transfers ranging from -0.004 to -0.08 (GeV/c)^2 at 6 GeV and from -0.002 to -0.06 (GeV/c)^2 at 5 GeV.

The experimental setup is shown schematically in Fig. 1. A bremsstrahlung beam from the DESY synchrotron hits a target of liquid H_2 (or D_2), 20 cm long. Since the energy of the recoiling nuclei is too small to be measured, only the scattered photons are registered. Photon energy and angles are measured in a pair spectrometer consisting of a 4 mm thick Al converter, one bending magnet and two telescopes equipped with 7 sparkchambers and one shower counter each. The energy resolution of the spectrometer was 1.3 % (fwhm).

Special care was taken to prepare the incoming photon beam so that it produced little halo at the converter position: The beam originated in a small $(2 \times 2 \text{ mm}^2)$ source and was shaped and cleaned by three collimators with subsequent clearing magnets. It was guided through vacuum wherever possible. The empty target rate varied between 2 % and 25 %, depending on the scattering angle. No events were recorded when the converter was removed.

The beam intensity and spectrum were continuously measured by a second pair spectrometer, placed downstream in the main beam. The intensity was also monitored by a thick-walled ionization chamber (quantameter). It was corrected for absorption between the experiment and the monitors. The systematic error for the intensity is $\pm 1.2 \%$.

Photons from electron Compton scattering were eliminated by their energy being less than 80 % of the maximum beam energy in the angular interval covered by the converter. Accidental and multiple track rates caused by this and other sources of background were lower than 1.2 %.

The contribution of inelastic hadronic reactions were separated by means of the different photon spectra they produce:

The energy spectrum of Compton scattered photons reproduces the sharp edge of the primary beam spectrum while the spectra of inelastic processes vanish smoothly at the end point. Fig. 2 demonstrates the different shapes.

Both Compton scattering and inelastic reactions were simulated by Monte Carlo calculations as a function of the photon energy k and the four-momentum transfer $|t|$.

Inelastic reactions considered are the reactions $\gamma p \rightarrow \pi^0 p$ with $\pi^0 \rightarrow \gamma\gamma$ and $\gamma p \rightarrow \eta p$ with $\eta \rightarrow \gamma\gamma$ (1,2). They lead to a spectrum known to about 20 % accuracy, which will be called B2 thereafter.

Further background contributions result from the reactions $\gamma p \rightarrow \gamma N^*$ with $N^*(1470)$, $N^*(1520)$ and $N^*(1688)$ (3), the processes $\gamma p \rightarrow \omega p$ with $\omega \rightarrow \gamma\pi^0$ (4), and multi pion production $\gamma p \rightarrow \gamma p + m\pi$ with $m \geq 1$ (3), giving a spectrum referred to as B1 below.

The sum of the Compton spectrum, B1 and B2 was then fitted to the measured spectrum, with the magnitudes of the Compton spectrum, of B1, and the end energy as free parameters. For obtaining the t -dependence, the end energy was then kept fixed, and the spectra were fitted for each t -bin separately.

The differential cross sections determined in this way are listed in Tab. 1 and shown in Fig.3a,b. Only statistical errors are shown. Systematic errors result mainly from the uncertainty of the background B2 (± 1 %) of the converter

position (1.5 %), and in the case of the 6 GeV data from the error in the telescope efficiencies (1.5 %). By quadratic addition to the normalization error we obtain a total systematic error of 2.5 % at 5 GeV and 3.6 % at 6 GeV.

A fit to our data of the form $d/dt = A \cdot \exp(Bt)$, as suggested by diffraction theory, yields the results shown in Tab. 2 (see curves in fig. 3a,b). The errors include statistical errors as well as the total systematic error.

The extrapolated forward cross sections are shown in fig. 4 as a function of the laboratory photon energy. They agree with earlier coincidence measurements in the same energy region^{7,5,6)}. For comparison, the solid curve shows the forward cross section as derived from total cross section measurements via the Optical Theorem and dispersion relations⁸⁾, assuming the spin-dependent amplitude to be zero. This predicted cross section is about 10 % higher than the new and some of the earlier measurements. Whether this difference is due to systematic errors in the underlying measurements, or to a failure of the straight-line extrapolation at very small angles, is unknown to us. The sign of the difference certainly argues against a sizeable contribution of the spin-dependent amplitude, since it would add to the prediction.

For comparison with the predictions of the vector dominance model, VDM, the forward cross sections have been calculated using the sum rule

$$\frac{d\sigma}{dt}(\gamma p \rightarrow \gamma p) = \left[\sum_V \frac{\alpha}{4} \frac{4\pi}{\gamma_V^2} \left(\frac{d\sigma}{dt}(\gamma p \rightarrow V p) \right)^{1/2} \right]^2$$

with recent values for the vector meson cross sections⁽⁹⁾ and the Orsay values for the coupling constants $\frac{\alpha}{4} \cdot \frac{4\pi}{\gamma_V^2}$ (10). Table 2 demonstrates the well known

discrepancy: The data are higher by about 40 % than the VDM predictions. This discrepancy can be removed by including the higher vector mesons $\rho'(1600)$, $\psi(3100)$ and $\psi'(3700)$ and by extending the VDM to the GVDM ⁽¹¹⁾.

The differential cross section for the deuteron (Fig. 3a,b) shows the transition from coherent scattering at low $|t|$ to incoherent scattering at higher $|t|$ values. Neglecting spin effects the cross section can be written in closure approximation as

$$\left. \frac{d\sigma}{dt} \right|_d = \frac{2\pi}{k^2} \left[|a_0|^2 (1 + F(t)) + |a_1|^2 (1 - F(t)) \right] \cdot G(t)$$

where k is the photon energy. $F(t)$ and $G(t)$ denote the deuteron form factor and the Glauber correction factor ⁽¹²⁾. a_0 and a_1 are the amplitudes of isospin 0 and 1 exchange. The influence of the Fermi motion ⁽¹³⁾ is smaller than the Glauber correction, according to our own calculations. The corresponding differential proton cross section is given by

$$\left. \frac{d\sigma}{dt} \right|_p = \frac{\pi}{k^2} (|a_0|^2 + |a_1|^2 + 2\text{Re}(a_0 a_1^*))$$

From the deuteron and the proton cross sections one can deduce the two isospin ratios $|a_1|^2 / |a_0 + a_1|^2$ and $\text{Re}(a_0 a_1^*) / |a_0 + a_1|^2$. By a fit to our experimental data (also shown in Fig. 3a,b) we obtain the values listed in Tab. 3. Systematic errors resulting mainly from the uncertainty in the B2 background component and in the precise converter position, amount to about half of the statistical errors, while normalization errors common to both targets should have no effect.

The isospin ratios depend however sensitively on the assumed shape of $F(t)$ and $G(t)$. We have used a deuteron wave function following Reid ⁽¹⁴⁾ and calculated $G(t)$ in the ρ -dominance approximation. If we analyse the data starting from a Hulthén wave function ⁽¹⁵⁾, we obtain consistent, although numerically different ratios. For comparison we have also calculated these parameters from the data of Boyarski et al. ⁽⁷⁾ using our Glauber corrections. The values are then changed slightly as shown in Tab. 3.

All the ratios are compatible with a vanishing or at least small isospin 1 exchange contribution to photon nucleon interaction. They are also compatible with the measured ⁽¹⁶⁾ ratio

$$\frac{\text{Im } a_1}{\text{Im } a_0} = \frac{\sigma(\gamma p) - \sigma(\gamma n)}{\sigma(\gamma p) + \sigma(\gamma n)}$$

as listed in Table 3, if one assumes equal real and imaginary parts of the a_1 amplitude as predicted for A_2 Regge exchange.

Table 1: Differential Compton-Cross section for hydrogen and deuterium at 5 GeV and 6 GeV. Also shown is the Glauber correction parametrized as $G(t) = 1 - X(t)$, calculated from the deuteron wave function following Reid ⁽⁵⁾

5 GeV	Hydrogen		Deuterium		
$-t$ (GeV/c) ²	$d\sigma/dt$ (H) $\mu\text{b}/(\text{GeV}/c)^2$	stat. error	$d\sigma/dt$ (D) $\mu\text{b}/(\text{GeV}/c)^2$	stat. error	$X(t)$
0.0016 - 0.0036	0.68	± 0.14	2.16	± 0.21	0.055
0.0036 - 0.0064	0.78	± 0.07	2.42	± 0.10	0.058
0.0064 - 0.0100	0.78	± 0.05	2.15	± 0.08	0.062
0.0100 - 0.0144	0.79	± 0.04	1.99	± 0.06	0.066
0.0144 - 0.0196	0.70	± 0.04	1.75	± 0.05	0.069
0.0196 - 0.0256	0.62	± 0.04	1.62	± 0.05	0.073
0.0256 - 0.0324	0.61	± 0.03	1.43	± 0.05	0.077
0.0324 - 0.0400	0.63	± 0.03	1.35	± 0.05	0.080
0.0400 - 0.0484	0.55	± 0.03	1.17	± 0.05	0.084
0.0484 - 0.0576	0.54	± 0.04	1.20	± 0.07	0.087

6 GeV	Hydrogen		Deuterium		
$-t$ (GeV/c) ²	$d\sigma/dt$ $\mu\text{b}/(\text{GeV}/c)^2$	stat. error	$d\sigma/dt$ (D) $\mu\text{b}/(\text{GeV}/c)^2$	stat. error	$X(t)$
0.0040 - 0.0052	0.69	± 0.17	2.56	± 0.39	0.063
0.0052 - 0.0092	0.81	± 0.06	2.17	± 0.14	0.067
0.0092 - 0.014	0.77	± 0.05	1.71	± 0.10	0.071
0.014 - 0.021	0.66	± 0.04	1.74	± 0.08	0.076
0.021 - 0.028	0.60	± 0.03	1.54	± 0.07	0.081
0.028 - 0.037	0.61	± 0.03	1.28	± 0.06	0.085
0.037 - 0.047	0.53	± 0.03	1.25	± 0.06	0.088
0.047 - 0.058	0.51	± 0.03	0.86	± 0.05	0.092
0.058 - 0.070	0.45	± 0.03	0.91	± 0.05	0.096
0.070 - 0.083	0.45	± 0.04	0.72	± 0.06	0.100

Table 2: Parameters of an exponential fit to the Compton cross section on hydrogen of the form $d\sigma/dt = A \cdot \exp(B \cdot t)$

	Photon energy GeV	$d\sigma/dt(0)$ $\mu\text{b}/(\text{GeV}/c)^2$	B (GeV/c) ⁻²
This experiment	5	0.82 ± 0.04	8.5 ± 1.5
	6	0.79 ± 0.04	8.6 ± 1.2
DESY ⁽⁵⁾	4 - 6.2	0.84 ± 0.08	5.7 ± 0.35
SLAC ⁽⁷⁾	8	0.82 ± 0.04	7.7 ± 0.5
VDM Prediction (see text)	5	0.46 ± 0.05	-
	6	0.44 ± 0.04	-

Table 3: *) Calculation with Hulthén-wave-function
 **) Analysis of the data with the deuteron form factor and the
 Glauber correction obtained from a wave function following
 Reid.

	$\frac{ a_1 ^2}{ a_0 + a_1 ^2}$	$\frac{\text{Re}(a_0 a_1^*)}{ a_0 + a_1 ^2}$
This experiment 5 GeV	0.13 ± 0.09 (0.08 ± 0.10)	$0. \pm 0.03$ $0.02 \pm 0.03)^*$
6 GeV	-0.12 ± 0.15 (-0.12 ± 0.15)	0.10 ± 0.04 $0.10 \pm 0.04)^*$
SLAC ⁽⁷⁾ 8 and 16 GeV	0.03 ± 0.10 (0.02 ± 0.12)	-0.043 ± 0.012 $0.02 \pm 0.02)^{**}$
This experiment and SLAC ⁽⁷⁾	0.08 ± 0.05	0.02 ± 0.01
DESY ⁽¹⁶⁾	$\frac{\text{Im } a_1}{\text{Im } a_0} = 0.042 \pm 0.008$	

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Figure Captions

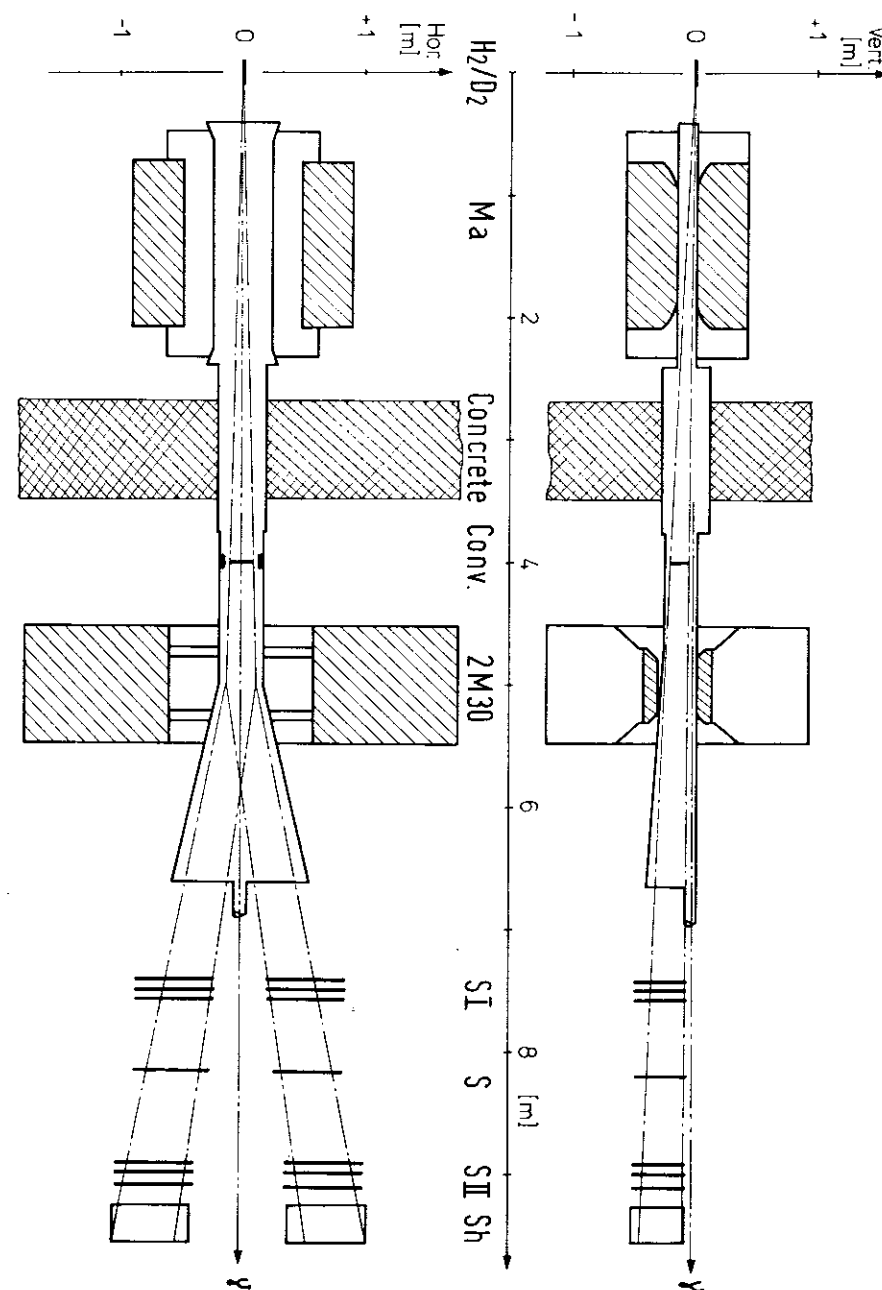
Fig. 1 Schematic view of the magnetic Compton spectrometer. Side view and top view. H_2/D_2 : Target; Ma: Cleaning magnet; Conv: Converter; 2M30: Analyzing magnet; SI, S, SII: Spark chambers; Sh: Shower counters.

Fig. 2 Reconstructed spectrum of photons scattered on protons at 6 GeV with $0.004 \leq |t| \leq 0.08 \text{ (GeV/c)}^2$. Also shown the result of a fit separating Compton- and background contributions.

Fig. 3 Differential cross sections for Compton scattering on hydrogen and deuterium at 5 and 6 GeV. Also shown the result of an exponential fit to the hydrogen data, and of a form factor fit to the deuteron data. see text.

Fig. 4 Forward Compton cross sections on hydrogen vs photon energy. Also shown is the expected value as calculated from the optical theorem including a real part⁽⁸⁾, the shaded area indicates the error of about 4 % in $\sigma_{\text{tot}}(\gamma p)$ ⁽¹⁶⁾.

Fig.1 Compton Pair Spectrometer



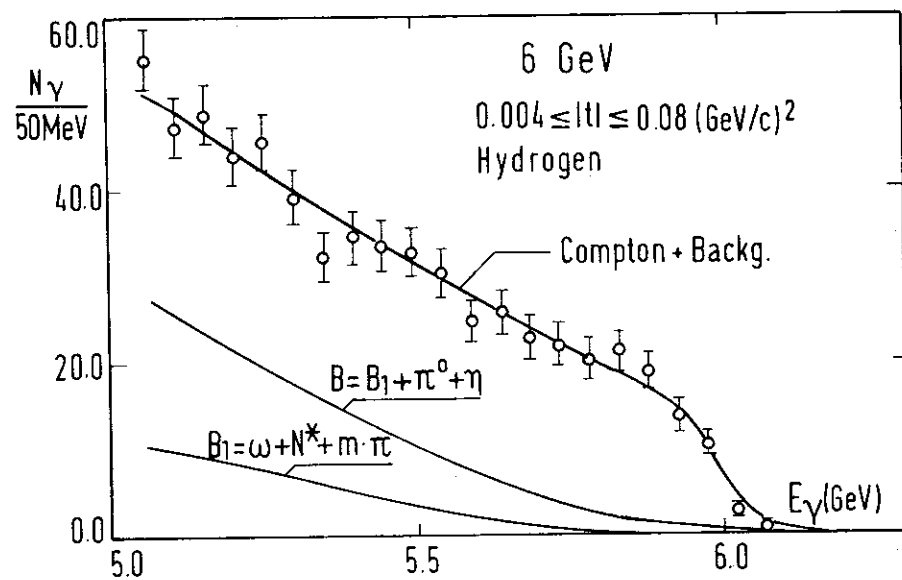


Fig.2 Reconstructed Photon Energy Spectrum

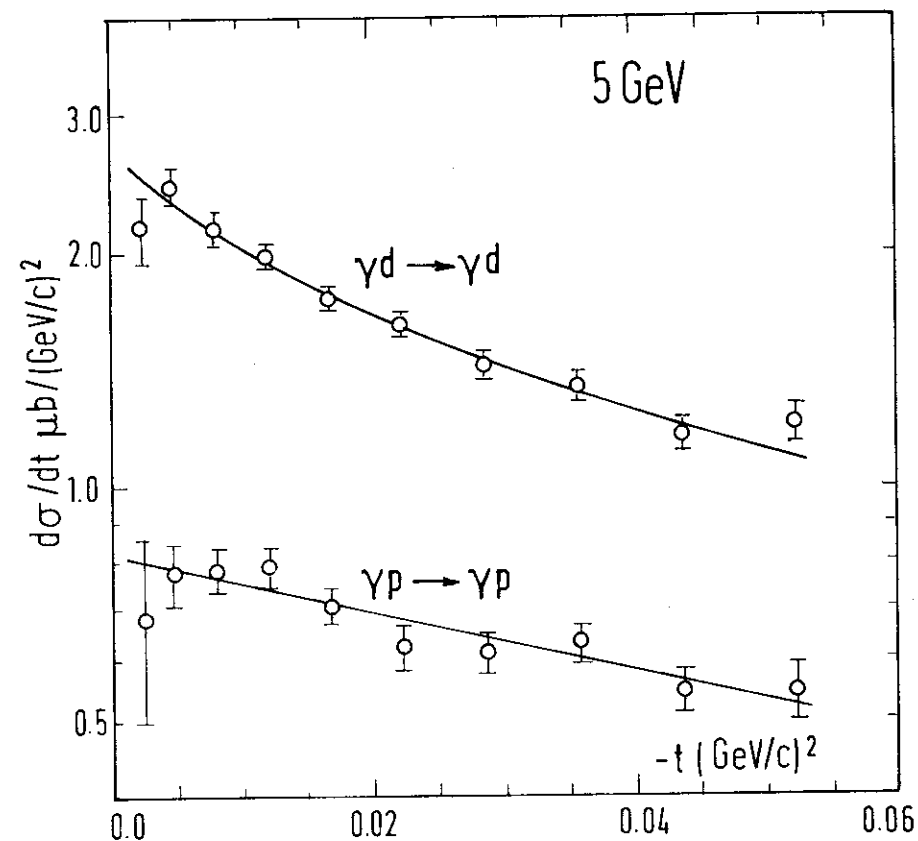


Fig.3a Compton Scattering on Hydrogen and Deuterium

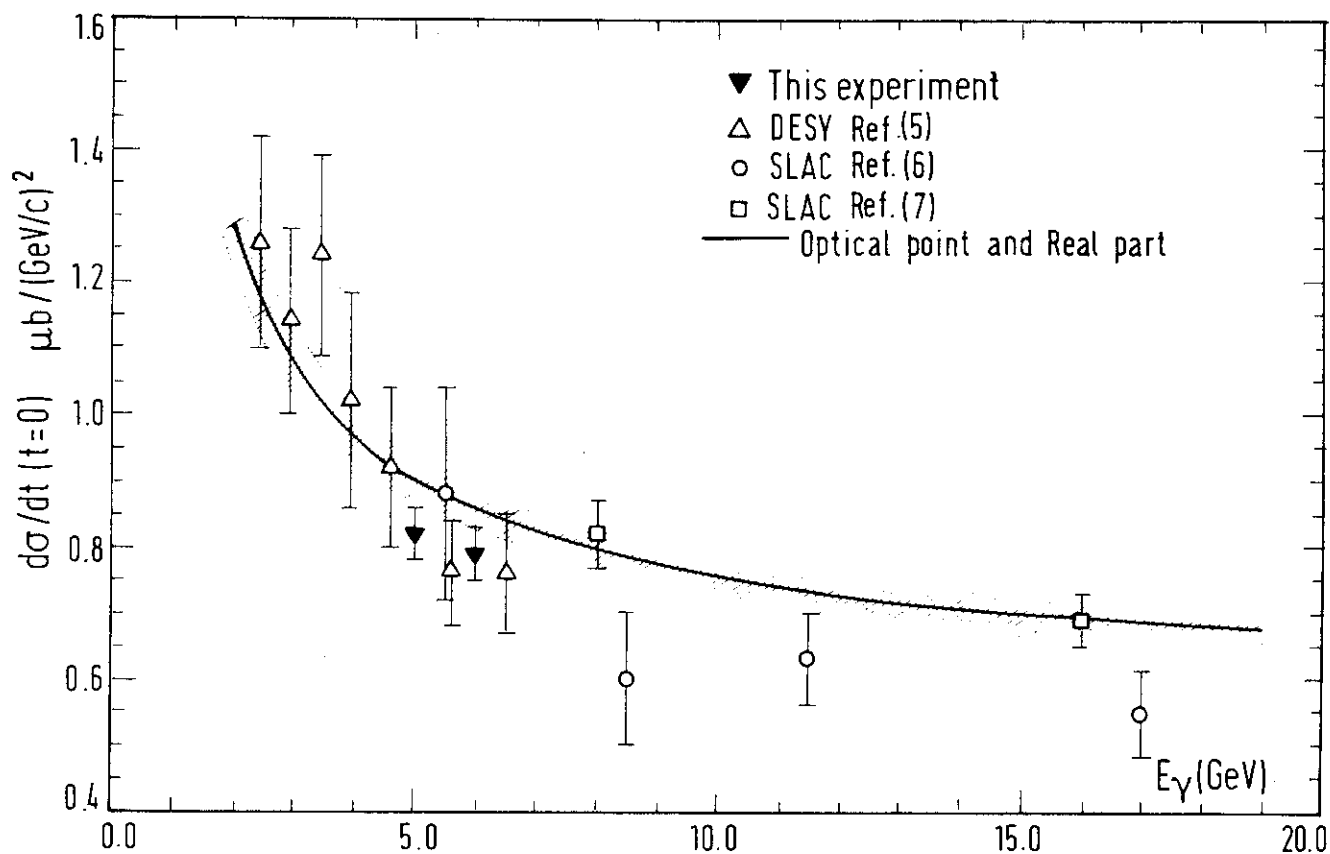


Fig.4 Differential forward Compton Cross Section on Hydrogen

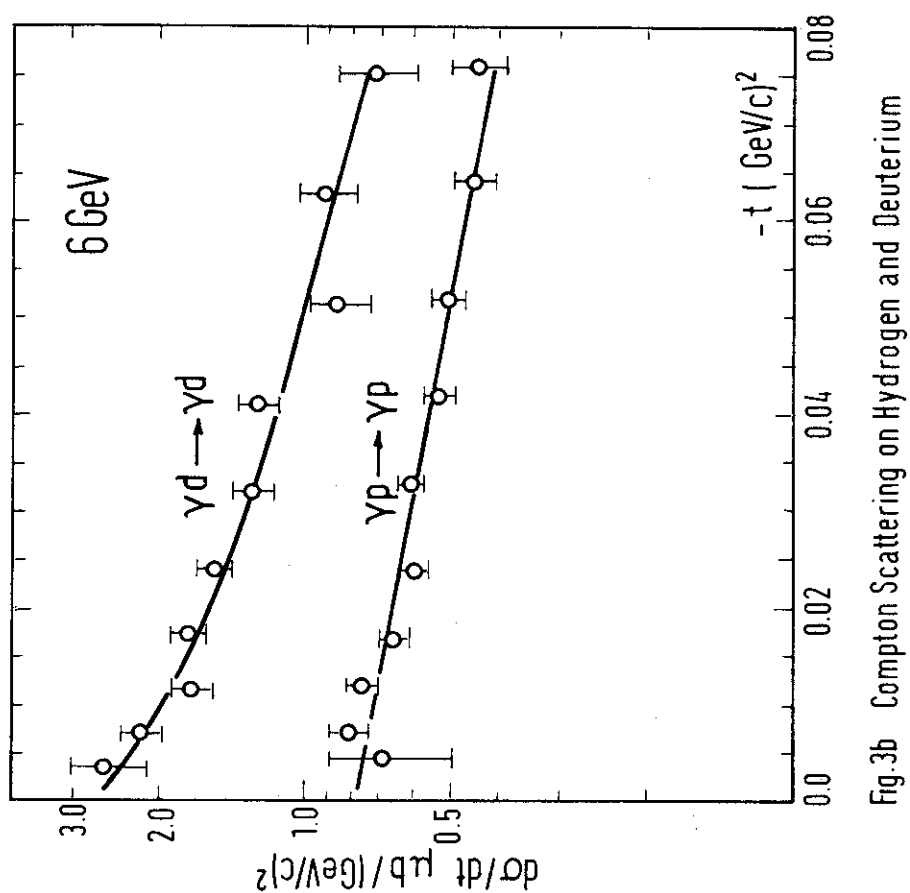


Fig.3b Compton Scattering on Hydrogen and Deuterium