Proton Compton Effect: A Measurement of the Electric and Magnetic Polarizabilities of the Proton

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We have measured the Compton-scattering cross section on hydrogen at 60° and 135° using monochromatic tagged photons spanning the energy between 32 and 72 MeV. These data, when analyzed with a low-energy expansion of the scattering cross-section formula, provide a determination of values for the electric and magnetic polarizabilities of the proton. We find, respectively, $\bar{\alpha}=(10.9\pm2.2\pm1.3)\times10^{-4}$ fm^3 and $\bar{\beta}=(3.3\mp2.2\mp1.3)\times10^{-4}$ fm^3, assuming the model-independent constraint $\bar{\alpha}+\bar{\beta}=14.2\times10^{-4}$ fm^3.

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The electric and magnetic polarizabilities, labeled α and β, respectively, measure the ease with which an electric or magnetic dipole moment can be induced in a composite system by static external electric or magnetic fields [1]. These structure constants are therefore fundamentally as important as the radius, the charge, and the magnetic moment of the system. However, in the case of the nucleon they are considerably less well known. With the high present-day interest in QCD-based theoretical descriptions of the nucleon, it is clear that the additional information represented by an accurate determination of its polarizabilities would be of substantial importance.

Simple constituent quark models [2] relate α to the size and energy scales of the proton, and experimental measurements for these quantities typically lead to values in the range $\alpha\sim10\times10^{-4}$ fm^3. The simplest bag-model calculations lead to similar values [3]. However, these results are possibly misleading, since these models suffer from the inherent difficulty that their size and energy scales are incompatible. Furthermore, only contributions due to excited states of the nucleon are included; potentially important contributions due to states of the pion-nucleon system are omitted. These deficiencies are partially remedied in a chiral bag model, where the valence quark core is surrounded by a pion cloud. Using this model, Weiner and Weise [4] reproduce both the size scale, which is largely determined by the pion cloud, and the energy scale, which is determined by the quark core. They find $\alpha\sim(7\text{–}9)\times10^{-4}$ fm^3; interestingly, only a small part of the result is due to excited states of the quark core, while the dominant contribution comes from the pion cloud.

The magnetic polarizability β is believed to be smaller than α due to a strong cancellation between the positive contribution of the low-lying $\Delta(1232)$ resonance and the negative contribution of virtual quark-antiquark pairs [1,2]. The degree to which the cancellation occurs is highly model dependent, and at this point in time even the sign of β is uncertain. Typically the calculations span the range $(-3\le\beta\le3)\times10^{-4}$ fm^3. An accurate determination of β would be of great value in constraining the model calculations.

Measurements of the proton polarizabilities have exclusively come from Compton-scattering experiments. These measurements rely on a theorem to establish a unique relation between a low-energy expansion of the Compton-scattering cross section and the static polarizabilities. For photon energies small compared to the pion mass, this expansion reads [1]

$$\frac{d\sigma}{d\Omega}(E,\theta)=\frac{d\sigma^{\rm pt}}{d\Omega}(E,\theta)-r_0\left[\frac{E'}{E}\right]^2\left[\frac{EE'}{(\hbar c)^2}\right]\left[\frac{\bar{\alpha}+\bar{\beta}}{2}(1+\cos\theta)^2+\frac{\bar{\alpha}-\bar{\beta}}{2}(1-\cos\theta)^2\right], \quad (1)$$

where E and E' are the energies of the incident and scattered photon, respectively; r_0 is the classical radius of the proton; and $d\sigma^{\rm pt}/d\Omega$ is the exact cross section for a structureless proton with an anomalous magnetic moment [5]. E and E' are related by the usual Compton formula. The quantities $\bar{\alpha}$ and $\bar{\beta}$ combine the effects of the static polarizabilities, α and β, respectively, with the well-known retardation corrections to $d\sigma^{\rm pt}/d\Omega$ [1]; they are the only unknown parameters in Eq. (1). The equation shows that the forward cross section is sensitive mostly to $\bar{\alpha}+\bar{\beta}$, whereas the backward cross section is sensitive mostly to $\bar{\alpha}-\bar{\beta}$.

Now the sum $\bar{\alpha}+\bar{\beta}$ is also constrained by a model-independent dispersion sum rule [6]:

$$\bar{\alpha}+\bar{\beta}=\frac{\hbar c}{2\pi^2}\int_{m_\pi c^2}^{\infty}\frac{\sigma_\gamma(E)\,dE}{E^2}=(14.2\pm0.03)\times10^{-4}\,{\rm fm}^3, \quad (2)$$

where $\sigma_\gamma(E)$ is the total photoabsorption cross section on the proton. The integral is evaluated using both the available experimental data and a reasonable theoretical ansatz for continuing the integral to infinite energy [7].

Thus, a combination of the above dispersion sum rule and a measurement of the scattering cross section at a backward angle can determine both $\bar{\alpha}$ and $\bar{\beta}$. Alternately, measurements at forward and backward angles can determine both $\bar{\alpha}$ and $\bar{\beta}$ as well as test the sum rule.

A common feature of previous experiments has been the use of continuous-energy bremsstrahlung photon beams and photon detectors having poor energy resolution. These factors have made it difficult to determine the incident photon flux accurately. Consequently, all but one of these experiments quote systematic uncertainties that are too large to provide meaningful constraints on the polarizabilities [8]. The exception is the experiment of Baranov *et al.* [9], who find $\bar{\alpha}=(10.7\pm1.1)\times10^{-4}\ \text{fm}^3$ and $\bar{\beta}=(-0.7\pm1.6)\times10^{-4}\ \text{fm}^3$. However, despite the small error bars and the claim of small systematic uncertainty, this result is problematic since it is inconsistent with the dispersion sum rule [Eq. (2)]. In the new measurement reported here, we improve significantly on the situation by using a monochromatic tagged photon beam and large NaI(Tl) photon detectors with high intrinsic resolution ($\Delta E/E \sim 3\%$). As shown below, the result is a considerable improvement on our experimental knowledge of the proton polarizabilities.

Electrons from the 100% duty factor accelerator MUSL-2 were incident on a 34-mg/cm^2 Al radiator foil. The post-bremsstrahlung electrons were momentum analyzed in a magnetic spectrometer and detected in a staircase array of 32 plastic scintillator counters, thereby tagging the associated photons and determining their energy. The photons were collimated and directed onto a 0.89-g/cm^2 target of liquid hydrogen contained in a thin-walled Mylar vessel. Scattering data were taken with the vessel both full and empty, in order to be able to subtract the events due to scattering in the Mylar. The beam intensity was about 3×10^7 tagged photons/sec. Photons scattered from the target were detected in one of the two large NaI detectors. These were positioned at scattering angles of 60° and 135°, respectively, and subtended a solid angle of about 0.05 sr each. The detectors were each surrounded by an anticoincidence plastic scintillator shield in order to identify and reject both charged particles coming from cosmic rays and electrons and positrons emerging from the target.

A valid event consisted of a time-correlated coincidence between an electron in a tagging counter and the associated photon in one of the NaI detectors. The incident photon flux was determined directly by counting the tagging electrons; calibration measurements were done in which each of the NaI detectors was separately put directly into the photon beam in order to determine the number of tagged photons per tagging electron. Data were taken between 32- and 72-MeV incident photon energy, in four steps, each covering a total tagged photon range of 8 MeV. In the off-line analysis the data were combined into two bins, each 4 MeV wide. A typical pulse-height spectrum in one of the NaI detectors is shown in Fig. 1; chance coincidences, as well as the contribution of the empty Mylar vessel, have been subtracted out.

The scattering cross section is related to the measured quantities by the following expression:

$$\frac{d\sigma}{d\Omega}=\frac{1}{\kappa\Omega}\left[\frac{Y_\gamma^s/N_e^s}{Y_\gamma^c/N_e^c}\right]. \tag{3}$$

The numerator and denominator of the bracketed expression are the number of detected tagged photons per tagging electron in the scattering and calibration measurements, respectively; these were determined by summing over the appropriate regions of the pulse-height spectra. The denominator, which calibrates the incident photon flux, was determined to an overall accuracy of $\pm1\%$, based on the spread in its measured value in a large number of distinct measurements. The number of target nuclei per unit area, κ, was determined to an accuracy of $\pm1\%$ using the measured geometrical thickness and the known density of liquid hydrogen, corrected for bubbling. The solid angle for detection of the scattered photon, Ω, was calculated to an accuracy of $\pm1.4\%$ using the known geometry and a Monte Carlo simulation of the experiment. Combining all the systematic errors in quadrature, we estimate that the systematic uncertainty in the absolute scale of our cross sections is $\pm2.0\%$. The resulting cross sections are shown in Fig. 2 along with their statistical errors. Further details of the experimental setup, data reduction, various corrections, and systematic errors can be found in the thesis of Federspiel [10].

In order to extract values for $\bar{\alpha}$ and $\bar{\beta}$, a least-squares minimization procedure was used in which the combinations $\bar{\alpha}+\bar{\beta}$ and $\bar{\alpha}-\bar{\beta}$ were adjusted to fit the theoretical cross section to the experimental data. Two different theoretical cross sections were used as the fitting function. First, we used the low-energy expansion (LEX) as expressed in Eq. (1), which is expected to be valid for pho-

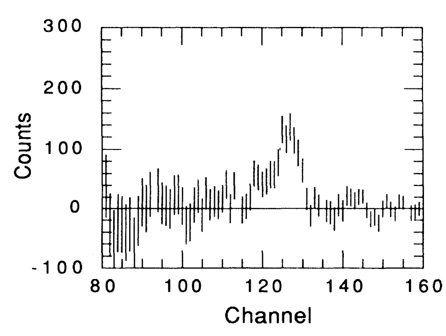

FIG. 1. Pulse-height spectrum from the scattering of 70-MeV tagged photons from hydrogen at 135°. Contributions to the scattering from chance coincidences and from the empty target vessel have been subtracted.

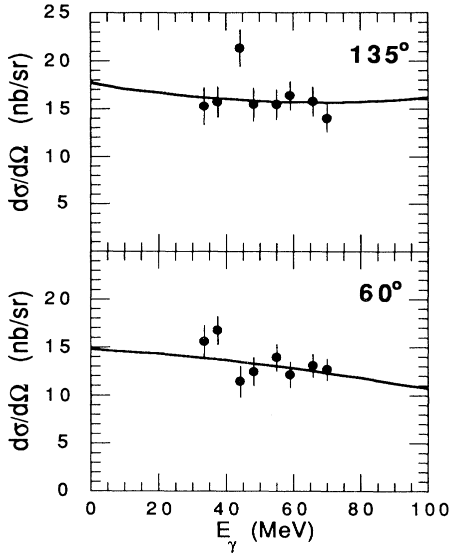

FIG. 2. Compton-scattering cross section on hydrogen obtained in the present experiment. The error bars include statistical contributions only. The curves are the theoretical cross sections implied by our measured polarizabilities using the theoretical cross section of L'vov.

ton energies sufficiently low compared to the pion mass. Second, we used an exact calculation due to L'vov [11], which is based on dispersion relations and in which the sum and difference of the polarizabilities are the only free parameters. For given values of the polarizabilities, the L'vov cross section reduces to the LEX for sufficiently low energies.

In Table I we show the results of four different fits to the data. We either allowed $\bar{\alpha}+\bar{\beta}$ to vary, or fixed it at the sum-rule value [Eq. (2)], for each of the two theoretical cross sections. The results are very sensitive to the absolute normalization of the cross sections. The systematic errors in Table I represent the effect of changing that normalization within our systematic uncertainty of $\pm 2.0\%$. The consistency of our fitted values of $\bar{\alpha}+\bar{\beta}$ with the sum-rule value gives us confidence in our normalization. The best value of $\bar{\alpha}-\bar{\beta}$ depends slightly on whether $\bar{\alpha}+\bar{\beta}$ is varied or fixed. We prefer holding $\bar{\alpha}+\bar{\beta}$ fixed, since there is no cause to doubt the validity of the dispersion sum rule. Further, the L'vov cross-section formula gives a somewhat smaller value than we get using the LEX. Since the range of validity of the LEX is not known with great certainty, and since the L'vov cross sections are in excellent agreement with recent Compton-scattering data on hydrogen between 150 and 300 MeV [12], we take as our final result the value given by the L'vov cross section. We therefore conclude

$$\begin{aligned} \bar{\alpha} &= (10.9 \pm 2.2 \pm 1.3) \times 10^{-4}\,\text{fm}^3, \\ \bar{\beta} &= (3.3 \mp 2.2 \mp 1.3) \times 10^{-4}\,\text{fm}^3. \end{aligned} \tag{4}$$

The first quoted error is statistical, while the second is systematic; the errors on $\bar{\alpha}$ and $\bar{\beta}$ are anticorrelated. The curves in Fig. 2 are the theoretical cross sections implied by these polarizabilities. As shown by Federspiel [10], these values are not consistent with the cross sections of Baranov *et al.* [9].

TABLE I. Values of the polarizabilities extracted from the present Compton-scattering data. The first quoted error is statistical, while the second is systematic. The quantity ν is the number of degrees of freedom in each fit.

Theory[a]	$(\bar{\alpha}+\bar{\beta})$ [b]	$(\bar{\alpha}-\bar{\beta})$ [b]	χ^2/ν
LEX	$12.2 \pm 3.5 \pm 1.5$	$9.1 \pm 4.0 \pm 2.0$	1.296 [c]
LEX	14.2 (fixed)	$8.7 \pm 4.0 \pm 2.4$	1.231 [d]
L'vov	$11.9 \pm 3.9 \pm 1.7$	$8.0 \pm 4.4 \pm 2.2$	1.305 [c]
L'vov	14.2 (fixed)	$7.6 \pm 4.3 \pm 2.5$	1.241 [d]

[a]LEX refers to the low-energy expansion, Eq. (1); L'vov refers to the full dispersion calculation of L'vov [11].
[b]The values are in units of 10^{-4} fm^3.
[c]The value of $\nu = 14$.
[d]The value of $\nu = 15$.

In a nonrelativistic treatment, α and $\bar{\alpha}$ are related by [1] $\bar{\alpha} = \alpha + e^2\langle r^2\rangle/3Mc^2$, where $\langle r^2\rangle$ is the mean-square charge radius of the proton. Our result for $\bar{\alpha}$ implies

$$\alpha = (7.0 \pm 2.2 \pm 1.3) \times 10^{-4}\,\text{fm}^3\ \text{(proton)}.$$

Recently a new measurement of the electric polarizability of the neutron has been reported by Schmiedmayer *et al.* [13]:

$$\alpha = (12.0 \pm 1.5 \pm 2.0) \times 10^{-4}\,\text{fm}^3\ \text{(neutron)}.$$

Such a large difference between the electric polarizabilities of the neutron and proton is entirely unexpected. In a valence quark model, approximate charge symmetry leads to near equality between α_n and α_p. Even in a chiral bag model, where α is due mainly to the pion cloud, Weiner and Weise [4] argue that α is dominated by those pion contributions that are equal for the neutron and proton. Evidently, new theoretical efforts will be needed to account for this large difference.

In the case of β we indeed observe a large cancellation, indicating that both the $\Delta(1232)$ resonance and the virtual quark-antiquark pairs are playing important roles in the scattering process. Despite this cancellation, our results provide the first definitive evidence that $\bar{\beta}$ is positive.

In summary, we have measured the Compton-scattering cross section on hydrogen at both forward and backward angles using a monochromatic tagged photon beam that spanned the energy range between 32 and 72 MeV. The low systematic uncertainties in this experiment represent a distinct improvement over previous experiments, allowing us to extract significantly more precise, internally consistent, values for the electric and magnetic polarizabilities of the proton. These values are in agreement with the constraint implied on $\bar{\alpha}+\bar{\beta}$ by Eq. (2), and have led to interesting comparisons to the experimental result for the neutron electric polarizability and to calculations of the proton magnetic polarizability.

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