First Extraction of a Spin Polarizability of the Proton

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A proton spin polarizability characterizing backward Compton scattering has been extracted from a dispersion analysis of data between 33 and 309 MeV. This backward spin polarizability, $\delta_\pi = [27.1 \pm 2.2(\text{stat} + \text{syst})^{+2.8}_{-2.4}(\text{model})] \times 10^{-4}$ fm^4, differs significantly from theoretical estimates and suggests a new contribution from the nonperturbative spin structure of the proton. This δ_π value removes an apparent inconsistency in the difference of charge polarizabilities extracted from data above π threshold. Our global result, $\overline{\alpha} - \overline{\beta} = [10.11 \pm 1.74(\text{stat} + \text{syst})^{+1.22}_{-0.86}(\text{model})] \times 10^{-4}$ fm^3, agrees with the previous world average of data below 155 MeV. Our value for $\overline{\alpha} + \overline{\beta} = [13.23 \pm 0.86(\text{stat} + \text{syst})^{+0.20}_{-0.49}(\text{model})] \times 10^{-4}$ fm^3 is consistent with a recent reevaluation of the Baldin sum rule. [S0031-9007(98)06009-8]

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Elastic photon (Compton) scattering from the proton is described by six helicity amplitudes. The leading corrections to the point scattering from the proton charge and magnetic moment are characterized by six polarizability parameters that are sensitive to the proton's internal structure. Two of these, the electric ($\overline{\alpha}$) and magnetic ($\overline{\beta}$) polarizabilities, measure the dynamic deformation of the constituent charge and magnetic moment distributions produced by the electromagnetic fields of the photon. The other four arise from the interaction of the photon fields with the constituent spins and so are sensitive to the proton's spin structure [1]. In this Letter we describe the first extraction of a particular linear combination of these spin polarizabilities that characterizes backward Compton scattering.

A low-energy expansion (LEX) of the Compton amplitudes to $O(E_\gamma^3)$ which includes the explicit dependence upon the two charge polarizabilities [2], $\overline{\alpha}$ and $\overline{\beta}$, gives a good description of unpolarized photon scattering data up to about 100 MeV [3,4]. Above this, Compton data deviate from these LEX expectations due to higher order effects. This has been taken into account in the analysis of a number of experiments [5–7] with the dispersion theory of L'vov [8], in which the key free parameter is the difference of the charge polarizabilities, $\overline{\alpha} - \overline{\beta}$. This has led to a consistent description of Compton scattering up to single-π production threshold ($E_\gamma \sim 150$ MeV lab), with a global average from all data [7] of $\overline{\alpha} - \overline{\beta} = 10.0 \pm 1.5(\text{stat} + \text{syst}) \pm 0.9(\text{model})$, in units of 10^{-4} fm^3.

Dispersion integrals relate the real parts of the scattering amplitude to energy-weighted integrals of their imaginary parts. In the L'vov theory [8], these are written as

$$\text{Re}A_i(\upsilon, t) = A_i^{\text{B}}(\upsilon, t) + \frac{2}{\pi}\,\text{P}\int_{\upsilon_0}^{\upsilon^{\max}} \frac{\upsilon'\,\text{Im}A_i(\upsilon', t)}{\upsilon'^2 - \upsilon^2}\,d\upsilon' + A_i^{\text{as}}(t)\,, \tag{1}$$

where $\upsilon = \frac{1}{4M}(s - u)$, M is the nucleon mass, and A_i^{B} denotes the Born contribution. Here unitarity fixes the $\text{Im}A_i$ as products of π-production multipoles, and these are used to calculate the principal value integral from threshold (υ_0) up to a moderately high energy ($\upsilon^{\max} = 1.5$ GeV). A_i^{as} is the residual asymptotic component. In Regge theory it is expected to be dominated by t-channel exchanges and is approximately υ independent. While four of the six Compton amplitudes are expected to converge with energy, the two associated with 180° photon helicity flip (the A_1 and A_2 amplitudes of [8]) could have appreciable asymptotic parts. In all previous analyses, t-channel π^0 exchange was assumed to completely dominate A_2^{as}, which is then evaluated in terms of the $F_{\pi^0\gamma\gamma}$ coupling. This ansatz left only A_1^{as} to be varied in a fit to data. Since $\overline{\alpha} - \overline{\beta}$ is determined by the $s - u = t = 0$ limit of the A_1 amplitude,

$$\overline{\alpha} - \overline{\beta} = -\frac{1}{2\pi}A_1^{\text{nB}}(0,0)\,, \tag{2}$$

where the nB superscript denotes the non-Born contributions from the *integral* and *asymptotic* parts of (1), this is equivalent to treating $\overline{\alpha} - \overline{\beta}$ as the single free parameter.

For energies below 2π-production threshold ($E_\gamma = 309$ MeV lab), unitarity provides an unambiguous connection between the imaginary parts of the Compton amplitudes in (1), the photopion multipoles, and pion-nucleon phase shifts. As E_γ approaches 309 MeV, these single π-production contributions to $\text{Im}A_i$ become very large, while 2π contributions are quite small below 400 MeV and at higher energies are suppressed by the energy denominator in (1). As a result, there is, in fact, very little freedom in the scattering amplitude below 309 MeV, and it is thus rather puzzling that applications of the L'vov dispersion analysis to scattering data up to Δ resonance energies appear to yield inconsistent results. While analysis of the $E_\gamma \le 155$ MeV portion of the 1993 data set from the Saskatchewan Accelerator Lab (SAL'93) yields an $\overline{\alpha} - \overline{\beta}$ value consistent with the global average [7], analyses of the full data set (extending up to 286 MeV) give significantly smaller results (Ref. [6] and Table II below). Even smaller $\overline{\alpha} - \overline{\beta}$ values result from extending the L'vov analysis to the new higher energy data sets from LEGS [9] and from Mainz [10,11] (see Table II below).

We propose that the weak link in all previous analyses is the ansatz of no additional contributions to the asymptotic part of the A_2 amplitude beyond those from π^0 *t-channel* exchange. We model corrections to A_2^{as} with an additional exponential t-dependent term having one free parameter, the derivative at $t = 0$. We fit all modern Compton data, and find this addition restores consistency in $\overline{\alpha} - \overline{\beta}$ values deduced from all data up to 2π threshold.

The physical significance of our additional A_2^{as} contribution becomes apparent when one examines the low-energy limit of the backward amplitude where the photon undergoes helicity flip. Expanding in powers of photon energy ω, the 180° Compton amplitude is

$$A_{\gamma,\gamma}(\pi) = A_{\mathrm{Born}} + \omega^2(\overline{\alpha} - \overline{\beta})(\vec{\varepsilon}\,' \cdot \vec{\varepsilon}) - i\omega^3(\delta_\pi)\vec{\sigma} \cdot (\vec{\varepsilon}\,' \times \vec{\varepsilon}) + O(\omega^{4,\cdots}). \quad (3)$$

Here, $\vec{\varepsilon}$ and $\vec{\varepsilon}\,'$ are the polarizations of the incident and final photon, respectively, and $\vec{\sigma}$ is the target spinor. The structure parameter δ_π, which we refer to as the backward spin polarizability, is a linear combination of the proton spin polarizabilities of Refs. [1] and [12], and is related to their definitions by $\delta_\pi = -(\gamma_1 + \gamma_2 + 2\gamma_4) = -1/2(\alpha_2 + \beta_2)$, respectively. In the L'vov dispersion analysis, δ_π is determined by the $s - u = t = 0$ limits of A_2 and A_5,

$$\delta_\pi = \frac{1}{2\pi M}\,[A_2^{\mathrm{nB}}(0,0) + A_5^{\mathrm{nB}}(0,0)]\,. \quad (4)$$

Evaluation of the dispersion integrals up to 1.5 GeV, together with the ansatz of t-channel π^0 exchange for A_2^{as}, results in $\delta_\pi = 36.6$ (in units of 10^{-4} fm^4), which is dominated by the π^0 contribution, $\frac{1}{2\pi M}A_2^{\mathrm{as}}(0,0) = 44.9$ [8,13]. (We have included t-channel η^0 exchange, but found this to have a very small effect, $+0.7$, owing to the large η mass and the small ηNN coupling [14].) A departure of δ_π from 36.6 would indicate additional components in $A_2^{\mathrm{as}}(0,0)$, and thus new contributions from the low-energy spin structure of the proton.

The backward spin polarizability in (3) enters in the part of the amplitude proportional to the target spinor, but interference with A_{Born} brings δ_π into the unpolarized cross section. We have varied our additional A_2^{as} parameter, together with A_1^{as}, in a fit to scattering data to determine the Compton amplitudes. Their $s - u = t = 0$ values then give δ_π and $\overline{\alpha} - \overline{\beta}$ for the proton.

We summarize here the key components in our analysis, deferring some details to a subsequent publication. We have studied Compton scattering up to 350 MeV, and have used the procedure described in [9] of simultaneously fitting π-production multipoles between 200 and 350 MeV, minimizing χ^2 for both (γ,γ) and (γ,π) observables. Outside the fitting interval we have taken the SM95 multipoles from [15]. We have used the same set of (γ,π) data as in [9], and have included the Compton data from LEGS [9], Mainz [10,11], SAL [6,7], the Max Plank Institute (MPI) [5], Illinois (Ill) [4], and Moscow [3]. (From the Moscow results we have used only the $\sim$90° data for reasons discussed in [7].) Relative cross section normalizations, weighted by the systematic uncertainties, were fitted following [16].

In addition to δ_π and $\overline{\alpha} - \overline{\beta}$, $\overline{\alpha} + \overline{\beta}$ can also be extracted in terms of the two nonhelicity-flip amplitudes that contribute to 0° scattering, $\overline{\alpha} + \overline{\beta} = -\frac{1}{2\pi}[A_3^{\mathrm{nB}}(0,0) + A_6^{\mathrm{nB}}(0,0)]$. A_3^{nB} and A_6^{nB} are dominated by the integrals in (1), with only A_6 having a small contribution from energies above 1.5 GeV which is varied in fitting the data. Alternatively, $\overline{\alpha} + \overline{\beta}$ can be fixed by the Baldin sum rule [17],

$$\overline{\alpha} + \overline{\beta} = \frac{1}{2\pi^2}\int_0^\infty \frac{\sigma^{\mathrm{tot}}}{\omega^2}\,d\omega\,, \quad (5)$$

where σ^{tot} is the total photoabsorption cross section. The right-hand side of (5) has been evaluated [18] from reaction data as 14.2 ± 0.3. This has been assumed in previous Compton analyses, although a reevaluation using recent absorption data has reported 13.7 ± 0.1 [19].

The polarizabilities obtained from the $s - u = t = 0$ values of the fitted amplitudes are summarized in Table I. The new *global* result (row 1) for $\overline{\alpha} - \overline{\beta}$ from all data below 2π threshold, 10.11 ± 1.74(stat + syst), is in excellent agreement with the previous average of low-energy data [7]. The fitted backward spin polarizability, $\delta_\pi = 27.1 \pm 2.2$, is substantially different from the π^0-dominated value of 36.6 that has been implicitly assumed in previous Compton analyses. The extracted $\overline{\alpha} + \overline{\beta} = 13.23 \pm 0.86$ is in agreement with the recent value for the sum rule of (5) from Ref. [19]. When $\overline{\alpha} + \overline{\beta}$ is fixed to the value from [19] (row 2), the changes to $\overline{\alpha} - \overline{\beta}$ and δ_π are negligible. The reduced χ^2 is $964/(692 - 36) = 1.47$ for the full database, and 1.15 per point for the Compton data alone. (Listed with the results in Table I are unbiased estimates of the uncertainties [20]. These are $\sqrt{\chi^2_{\mathrm{df}}}$ larger than the standard deviation which encompasses both statistical and systematic scale uncertainties.)

We have examined the effect of including Compton data up to 350 MeV, since 2π production is still quite small below this energy. However, since the polarizabilities enter only the real part of the Compton amplitude,

TABLE I. The global result for the proton polarizabilities (row 1), together with variations from using Eq. (5) as a constraint and from expanding the fit to 350 MeV.

E_γ^{max} (MeV)	$\overline{\alpha} + \overline{\beta}$ (10^{-4} fm^3)	$\overline{\alpha} - \overline{\beta}$ (10^{-4} fm^3)	δ_π (10^{-4} fm^4)
309	13.23 ± 0.86	10.11 ± 1.74	27.1 ± 2.2
309	13.7 fixed	10.45 ± 1.58	26.5 ± 1.9
350	14.39 ± 0.87	10.99 ± 1.70	25.1 ± 2.1

which unitarity forces to zero at the peak of the P_{33} Δ resonance, the additional 309–350 MeV data provide only marginal constraints on the polarizabilities. This expanded fit, row 3 in Table I, yields a slightly larger $\chi^2_{df}(1.57)$ and extracted polarizabilities which overlap the global results of row 1.

In Table II we show the effect of the backward spin polarizability on the value for $\overline{\alpha} - \overline{\beta}$ when each of the Compton data sets used in the global fit is analyzed separately. The results in the third and fourth columns assume $\delta_\pi = 36.6$. Column 3 uses SM95 multipoles from [15] and $\overline{\alpha} + \overline{\beta} = 14.2$ from [18], while the column 4 fits use multipoles from [9] and $\overline{\alpha} + \overline{\beta} = 13.7$ from [19]. In both cases, $\overline{\alpha} - \overline{\beta}$ values deduced from the three high energy data sets (LEGS'97, Mainz'96, and SAL'93) are completely inconsistent with the lower energy measurements. When δ_π is fixed to 26.5, the fitted value from Table I (row 2), consistency among the $\overline{\alpha} - \overline{\beta}$ values is restored (column 5). Significant changes to $\overline{\alpha} - \overline{\beta}$ occur mainly in the high-energy results, with the notable exception of the MPI'92 data which were taken at 180° where the effect of δ_π is maximal. In the backward unpolarized cross section, the square of the amplitude in (3), the leading term containing δ_π is [12,21]

$$-8\pi\mu_N^2(2 + 4\kappa + \kappa^2)\delta_\pi\omega^4, \qquad (6)$$

where κ is the anomalous magnetic moment of the target and μ_N is a nuclear magneton. Thus, the reduction of δ_π from 37 to 27 raises the 180° cross section and improves the consistency of the MPI'92 results. This provides the missing correction anticipated in [12].

The sensitivity of the high-energy cross sections to δ_π is illustrated in Fig. 1. The solid curves show our global result, with fitting uncertainties denoted by shaded bands. Curves denoted by plus signs use the old π^0-dominated value for δ_π. The effect of lowering $\overline{\alpha} - \overline{\beta}$ to 1.7 is shown as dashed curves. If both $\overline{\alpha} - \overline{\beta}$ and δ_π are changed to 1.7 and 36.6, respectively (the LEGS solution in Table II, column 4), the predicted cross sections are very close to the solid curves. However, this degeneracy is absent in the $1/2(d\sigma_\parallel - d\sigma_\perp)$ spin difference, as shown with the LEGS'97 data in the top panel of Fig. 1 for $E_\gamma = 287$ MeV. This spin difference is sensitive to $\overline{\alpha} - \overline{\beta}$ but completely independent of δ_π. Although the limited statistical accuracy of the polarization difference precludes determining $\overline{\alpha} - \overline{\beta}$ from this observable alone, it does provide a useful decoupling of $\overline{\alpha} - \overline{\beta}$ and δ_π.

We have studied the variations in the extracted polarizabilities that result from changing the assumptions used to compute the Compton dispersion integrals, such as the π^0 exchange coupling, multipion photoproduction, and the form of asymptotic contributions [8], particularly the new term added to A_2^{as}, as well as the parametrization of the

TABLE II. Values for $\overline{\alpha} - \overline{\beta}$ deduced from different Compton data sets assuming the previous π^0-dominated value for δ_π (36.6) and the new fitted value from Table I, row 2 ($\delta_\pi = 26.5$). Pion multipole solutions are listed in the top row, with the last column using the fit of Table I, row 2, which included all of these Compton data. For the analyses of individual data sets in the ($\delta_\pi = 36.6$) columns, cross sections were held at their published values, while in the last column normalization scales were fixed from the Table I fit.

(γ,π) multipoles		SM95 [15]	LEGS [9]	Fitted
δ_π (10^{-4} fm^4)		36.6	36.6	26.5
$\overline{\alpha} + \overline{\beta}$ (10^{-4} fm^3)		14.2	13.7	13.7
Data set	E_γ^{max} (MeV)		$\overline{\alpha} - \overline{\beta}$ (10^{-4} fm^3)	
LEGS'97	309	-0.6 ± 0.5	1.7 ± 0.5	9.3 ± 0.7
Mainz'96	309	-1.3 ± 3.4	-4.3 ± 3.0	8.4 ± 4.5
SAL'93	286	4.4 ± 0.6	3.8 ± 0.6	11.4 ± 0.8
SAL'95	145	10.3 ± 0.9	10.1 ± 0.9	11.5 ± 1.0
MPI'92	132	7.3 ± 2.7	6.9 ± 2.7	12.5 ± 3.1
Moscow'75	110	8.2 ± 2.7	8.5 ± 2.7	11.7 ± 2.8
Ill'91	70	11.1 ± 4.3	11.1 ± 4.3	12.1 ± 4.3

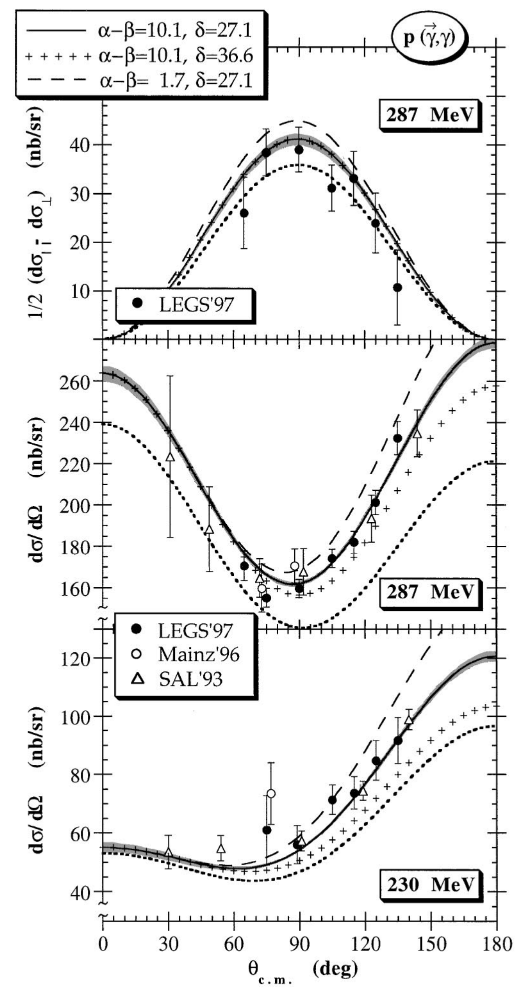

FIG. 1. Predictions from dispersion calculations at 230 and 287 MeV, compared to data from Refs. [6,9–11]. Solid curves are the global fit of Table I, row 1, with fitting uncertainties indicated by the shaded bands. Plus signs result from increasing δ_π and dashes from decreasing $\overline{\alpha} - \overline{\beta}$, as indicated. Dotted curves are predictions from [11,22].

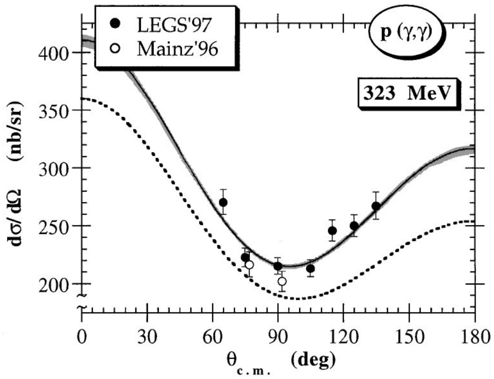

FIG. 2. The solid curve shows the fit of Table I, row 3, with uncertainties indicated by the shaded band. The dotted curve is the prediction from [11,22].

fitted (γ, π) amplitude [9]. Combining these model uncertainties in quadrature leads to our final results:

$$\delta_\pi = [27.1 \pm 2.2^{+2.8}_{-2.4}(\text{model})] \times 10^{-4}\ \text{fm}^4,$$

$$\overline{\alpha} - \overline{\beta} = [10.11 \pm 1.74^{+1.22}_{-0.86}(\text{model})] \times 10^{-4}\ \text{fm}^3,$$

$$\overline{\alpha} + \overline{\beta} = [13.23 \pm 0.86^{+0.20}_{-0.49}(\text{model})] \times 10^{-4}\ \text{fm}^3,$$

where the first error combines stat + syst uncertainties.

An alternative description of Compton scattering at Δ resonance energies has recently been published [11,22]. Fixing the proton polarizabilities to $\delta_\pi = 36.6$, $\overline{\alpha} - \overline{\beta} = 10.0$, and $\overline{\alpha} + \overline{\beta} = 14.2$ in the L'vov calculation, and fitting the 75° and 90° Mainz Compton data, these authors have proposed that the resonant part of the $M_{1+}^{3/2}$ photopion multipole be lowered by 3% from the SM95 solution of [15]. The predictions from their prescription are shown as the dotted curves in Fig. 1, as well as in Fig. 2 where the cross sections at the Δ peak are plotted. This prescription significantly underpredicts the large angle data from both LEGS and SAL. (In fact, our fitted $M_{1+}^{3/2}$ multipole, as well as that of [9], is very close to SM95.)

In summary, we have introduced a single additional parameter into the L'vov dispersion theory and have determined the Compton helicity amplitudes in a fit to scattering data from 33 to 309 MeV. The dispersion integrals require data over a large dynamic range to fix the $s - u = t = 0$ limits of the amplitudes, which then determine the proton polarizabilities δ_π, $\overline{\alpha} - \overline{\beta}$, and $\overline{\alpha} + \overline{\beta}$. The backward spin polarizability, δ_π, is most sensitive to Compton data above π threshold. The corresponding $\overline{\alpha} - \overline{\beta}$ is consistent with the previous *world* average [7] that, without our modification to δ_π, had been restricted to data below 155 MeV. The fitted $\overline{\alpha} + \overline{\beta}$ is consistent with the new value for the Baldin sum rule [19]. The extracted δ_π is substantially reduced from the π^0-dominated value that had been assumed in previous analyses, and indicates an unanticipated contribution from the nonperturbative spin structure of the proton. At present, there are no viable calculations of this quantity. Although chiral perturbation theory cannot be expected to directly predict Compton observables at the high energies included in this dispersion analysis, it should be able to reproduce the polarizabilities obtained by evaluating the fitted amplitudes at $s - u = t = 0$. However, existing $O(\omega^3)$ calculations are close to the π^0-dominated value and completely inconsistent with our result for δ_π [12,21]. Clearly, work is needed to extend these to higher order.

We have also investigated the sensitivity of other observables to δ_π, and several beam-target double-polarized cross sections are expected to have 2 to 3 times the sensitivity of unpolarized measurements. Such experiments are expected in the near future. However, the prospects are particularly intriguing for the neutron since, in a LEX, the leading terms in $\overline{\alpha}$ and $\overline{\beta}$ are proportional to charge and drop out [23]. As a result, the contribution in (6) enters at the same order as $\overline{\alpha}$ and $\overline{\beta}$, so that the cross sections should be noticeably affected by the neutron's backward spin polarizability even at low energies.

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[1] S. Ragusa, Phys. Rev. D **47**, 3757 (1993).
[2] V. A. Petrun'kin, Sov. J. Part. Nucl. **12**, 278 (1981).
[3] P. S. Baranov *et al.*, Sov. J. Nucl. Phys. **21**, 355 (1975).
[4] F. J. Federspiel *et al.*, Phys. Rev. Lett. **67**, 1511 (1991).
[5] A. Zieger *et al.*, Phys. Lett. B **278**, 34 (1992).
[6] E. L. Hallin *et al.*, Phys. Rev. C **48**, 1497 (1993).
[7] B. E. MacGibbon *et al.*, Phys. Rev. C **52**, 2097 (1995).
[8] A. I. L'vov, Sov. J. Nucl. Phys. **34**, 597 (1981); A. I. L'vov *et al.*, Phys. Rev. C **55**, 359 (1997).
[9] LEGS Collaboration, G. Blanpied *et al.*, Phys. Rev. Lett. **79**, 4337 (1997); **76**, 1023 (1996).
[10] C. Molinari *et al.*, Phys. Lett. B **371**, 181 (1996).
[11] J. Peise *et al.*, Phys. Lett. B **384**, 37 (1996).
[12] D. Babusci, G. Giordano, and G. Matone, Phys. Rev. C **55**, R1645 (1997).
[13] Similar values have been obtained with other pion multipoles; D. Drechsel *et al.*, nucl-th/9710029.
[14] T. Feuster and U. Mosel, nucl-th/9708051.
[15] R. Arndt, I. Strakovsky, and R. Workman, Phys. Rev. C **53**, 430 (1996).
[16] G. D'Agostini, Nucl. Instrum. Methods Phys. Res., Sect. A **346**, 306 (1994).
[17] A. M. Baldin, Nucl. Phys. **18**, 310 (1960).
[18] M. Damashek and F. J. Gilman, Phys. Rev. D **1**, 1319 (1970).
[19] D. Babusci, G. Giordano, and G. Matone, Phys. Rev. C **57**, 291 (1998).
[20] J. R. Wolberg, *Prediction Analysis* (Van Nostrand Co., New York, 1967), pp. 54–66.
[21] T. Hemmert, B. Holstein, J. Kambor, and G. Knöchlein, nucl-th/9709063.
[22] A. Hünger *et al.*, Nucl. Phys. **A620**, 385 (1997).
[23] A. I. L'vov, Sov. J. Nucl. Phys. **42**, 583 (1985).