Recoil Polarization for Delta Excitation in Pion Electroproduction

J. J. Kelly,¹ R. E. Roché,² Z. Chai,³ M. K. Jones,⁴ O. Gayou,⁵ A. J. Sarty,⁶ S. Frullani,⁶ K. Aniol,⁷ E. J. Beise,¹ F. Benmokhtar,⁸ W. Bertozzi,³ W. U. Boeglin,⁹ T. Botto,¹⁰ E. J. Brash,¹¹ H. Breuer,¹ E. Brown,¹² E. Burtin,¹³ J. R. Calarco,¹⁴ C. Cavata,¹³ C. C. Chang,¹ N. S. Chant,¹ J.-P. Chen,⁴ M. Coman,⁹ D. Crovelli,⁸ R. De Leo,⁶ S. Dieterich,⁶ S. Escoffier,¹³ K. G. Fissum,¹⁵ V. Garde,¹⁶ F. Garibaldi,⁶ S. Georgakopoulos,¹⁰ S. Gilad,³ R. Gilman,⁸ C. Glashausser,⁸ J.-O. Hansen,⁴ D. W. Higinbotham,³ A. Hotta,¹⁷ G. M. Huber,¹¹ H. Ibrahim,¹⁸ M. Iodice,⁶ C. W. de Jager,⁴ X. Jiang,⁸ A. Klimenko,¹⁸ S. Kozlov,¹¹ G. Kumbartzki,⁸ M. Kuss,⁴ L. Lagamba,⁶ G. Laveissière,¹⁶ J. J. LeRose,⁴ R. A. Lindgren,¹⁹ N. Liyanage,⁴ G. J. Lolos,¹¹ R. W. Lourie,²⁰ D. J. Margaziotis,⁷ F. Marie,¹³ P. Markowitz,⁹ S. McAleer,² D. Meekins,² R. Michaels,³ B. D. Milbraith,²¹ J. Mitchell,⁴ J. Nappa,⁸ D. Neyret,¹³ C. F. Perdrisat,²² M. Potokar,²³ V. A. Punjabi,²⁴ T. Pussieux,¹³ R. D. Ransome,⁸ P. G. Roos,¹ M. Rvachev,³ A. Saha,⁴ S. Sirca,³ R. Suleiman,³ S. Strauch,⁸ J. A. Templon,¹² L. Todor,¹⁸ P. E. Ulmer,¹⁸ G. M. Urciuoli,⁶ L. B. Weinstein,¹⁸ K. Wijesooriya,²⁵ B. Wojtsekhowski,⁴ X. Zheng,³ and L. Zhu³

(The Jefferson Laboratory E91011 and Hall A Collaborations)

¹Department of Physics, University of Maryland, College Park, Maryland 20742, USA
²Florida State University, Tallahassee, Florida 32306, USA
³Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
⁴Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA
⁵Saint Mary’s University, Halifax, Nova Scotia, Canada B3H 3C3
⁶Istituto Nazionale di Fisica Nucleare, Sezione Sanità and Istituto Superiore di Sanità, Physics Laboratory, 00161 Roma, Italy
⁷California State University Los Angeles, Los Angeles, California 90032, USA
⁸Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854, USA
⁹Florida International University, Miami, Florida 33199, USA
¹⁰University of Athens, Athens, Greece
¹¹University of Regina, Regina, Saskatchewan, Canada S4S 0A2
¹²University of Georgia, Athens, Georgia 30602, USA
¹³CEA Saclay, F-91191 Gif-sur-Yvette, France
¹⁴University of New Hampshire, Durham, New Hampshire 03824, USA
¹⁵University of Lund, Box 118, SE-221 00 Lund, Sweden
¹⁶Université Blaise Pascal Clermont Ferrand et CNRS/IN2P3 LPC 63, 177 Aubière Cedex, France
¹⁷University of Massachusetts, Amherst, Massachusetts 01003, USA
¹⁸Old Dominion University, Norfolk, Virginia 23529, USA
¹⁹University of Virginia, Charlottesville, Virginia 22901, USA
²⁰Renaissance Technologies Corporation, Setauket, New York 11733, USA
²¹Eastern Kentucky University, Richmond, Kentucky 40475, USA
²²College of William and Mary, Williamsburg, Virginia 23187, USA
²³University of Ljubljana, Kongresni trg 12, SI-1000 Ljubljana, Slovenia
²⁴Norfolk State University, Norfolk, Virginia 23504, USA
²⁵University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

(Dated: May 23, 2005)

We measured angular distributions of recoil-polarization response functions for neutral pion electroproduction for \( W = 1.23 \) GeV at \( Q^2 = 1.0 \) (GeV/c)^2, obtaining 14 separated response functions plus 2 Rosenbluth combinations; of these, 12 have been observed for the first time. Dynamical models do not describe quantities governed by imaginary parts of interference products well, indicating the need for adjusting magnitudes and phases for nonresonant amplitudes. We performed a nearly model-independent multipole analysis and obtained values for \( \text{Re} S_{1+}/M_{1+} = -(6.84 \pm 0.15)\% \) and \( \text{Re} E_{1+}/M_{1+} = -(2.91 \pm 0.19)\% \) that are distinctly different from those from the traditional Legendre analysis based upon \( M_{1+} \) dominance and \( \ell_0 \leq 1 \) truncation.

PACS numbers: 14.20.Gk,13.60.Le,13.40.Gp,13.88.+e

Insight into QCD-inspired models of hadron structure can be obtained by studying the properties of the nucleon and its low-lying excited states using electromagnetic reactions with modest spacelike four-momentum transfer, \( Q^2 \). In the very simplest models, quark-quark interactions with SU(6) spin-flavor symmetry suggest that the dominant configuration for the nucleon consists of three quarks in an S-state with orbital and total angular momenta \( L = 0 \) and \( J = 1/2 \), while the lowest excited state, the \( \Delta \) resonance at \( M_\Delta = 1.232 \) GeV with \( J = 3/2 \), is reached by flipping the spin of a single quark and leaving \( L = 0 \). Thus, the pion electroproduction reaction for invariant mass \( W \approx M_\Delta \) is dominated by the \( M_{1+} \) multipole amplitude. However, the \( M_\Delta - M_N \) mass split-
ing and the nonzero neutron electric form factor clearly demonstrate that SU(6) symmetry is broken by color hyperfine interactions that introduce D-state admixtures with \( L = 2 \) into these wave functions \([1]\). Although quadrupole configurations cannot be observed directly in elastic electron scattering by the nucleon, their presence in both wave functions contributes to \( S_{1+} \) and \( E_{1+} \) multipole amplitudes for electroexcitation of the \( \Delta \). Additional contributions to these smaller multipoles may also arise from meson and gluon exchange currents between quarks \([2]\) or coupling to the pion cloud outside the quark core \([3,4]\). Recently, it has also become possible to calculate \( N \) to \( \Delta \) transition form factors using lattice QCD, albeit in quenched approximation \([5]\).

The relative strength of the quadrupole amplitudes is normally quoted in terms of the ratios \( \text{SMR} = \text{Re}S_{1+/M_{1+}} \) and \( \text{EMR} = \text{Re}E_{1+/M_{1+}} \) evaluated for isospin \( 3/2 \) at \( W = M_\Delta \), but isospin analysis would require data for the \( n\pi^+ \) channel also. Fortunately, model calculations show that the isospin 1/2 contribution to these ratios is almost negligible. For example, one obtains (SMR, EMR) = \((-6.71\%, -1.62\%)\) for isospin 3/2 compared with \((-6.73\%, -1.65\%)\) for the \( p\pi^0 \) channel using MAID2003 \([6]\) at \( Q^2 = 1 \) (GeV/c)^2. Therefore, we quote results for the \( p\pi^0 \) channel without making model-dependent corrections for the isospin 1/2 contamination.

Most previous measurements of the quadrupole amplitudes for \( \Delta \) electroexcitation fit Legendre coefficients to angular distributions of the unpolarized cross section for pion production and employ a truncation that assumes: 1) only partial waves with \( \ell_\pi \leq 1 \) contribute and 2) terms not involving \( M_{1+} \) can be omitted. However, a more detailed analysis using models shows that neither assumption is sufficiently accurate \([7]\). Therefore, it is important to obtain data that are complete enough for nearly model-independent multipole analysis without relying upon \( sp \) truncation or \( M_{1+} \) dominance.

More detailed information about the nonresonant background can be obtained from polarization measurements that are sensitive to the relative phase between resonant and nonresonant amplitudes. This phase information is needed to test dynamical models that attempt to distinguish between the intrinsic properties of a resonance and the effects of rescattering. A few previous measurements of recoil polarization have been made for low \( Q^2 \) with the proton parallel to the momentum transfer \( \vec{q} \), but their kinematic coverage is quite limited. Several recent measurements of beam analyzing power have also been made \([10,11,12]\). Those experiments demonstrated that recent dynamical models do not describe the nonresonant background well. More generally, there are 18 independent response functions for the \( p(\vec{q}, \vec{q})\vec{p}p^0 \) reaction, of which half are sensitive to real and half to imaginary parts of products of multipole amplitudes \([13]\). In this Letter we report angular distributions for 14 separated response functions plus 2 Rosenbluth combinations for \( W = 1.23 \) GeV at \( Q^2 = 1.0 \) (GeV/c)^2 that are sufficiently complete to perform a phenomenological multipole analysis; twelve of these response functions are obtained here for the first time. Data for a wider range of \( W \) will be presented later in a more detailed paper.

The observables for recoil polarization can be resolved into response functions according to

\[
\vec{\sigma} = \nu_0 [\nu_L R_L + \nu_T R_T + \nu_{LT} R_{LT} \sin \theta \cos \phi] \\
\vec{\sigma} = \nu_0 [\nu_L' R_L' \sin \theta \sin \phi] \\
\vec{\sigma} = \nu_0 [\nu_L R_L + \nu_T R_T^0 \sin^2 \theta \cos 2\phi] \\
\vec{\sigma} = \nu_0 [\nu_L R_L' \sin \theta \sin \phi + \nu_{TT} R_{TT}^0 \sin \theta \cos 2\phi] \\
\vec{\sigma} = \nu_0 [\nu_L R_L \sin \theta \sin \phi] \\
\vec{\sigma} = \nu_0 [\nu_L R_L' \sin \theta \sin \phi] \\
\vec{\sigma} = \nu_0 [\nu_L R_L' \sin \theta \sin \phi + \nu_{TT} R_{TT}^0 \sin \theta \cos \phi] \\
\vec{\sigma} = \nu_0 [\nu_L R_L \sin \theta \sin \phi + \nu_{TT} R_{TT}^0 \sin \theta \cos \phi] \\
\vec{\sigma} = \nu_0 [\nu_L R_L' \sin \theta \sin \phi + \nu_{TT} R_{TT}^0 \sin \theta \cos \phi]
\]

where \( \vec{\sigma} \) is the virtual \( \gamma N \) unpolarized cm cross section, \( A \) is the beam analyzing power, and \( P \) and \( P' \) are helicity-independent and helicity-dependent polarizations expressed in terms of longitudinal, normal, and transverse basis vectors \( \ell, \ell' \propto \vec{q} \times \vec{q}, \ell' \propto \vec{n} \times \vec{q} \). Here \( \vec{q} \) is the momentum transfer in the lab and \( \vec{p}_N \) is the final nucleon momentum in the \( \pi N \) cm frame. The response functions, \( R \), depend upon \( W, Q^2 \), and \( \cos \theta \), where \( \theta \) is the pion angle relative to \( \vec{q} \) in the cm frame; subscripts \( L \) and \( T \) represent longitudinal and transverse polarization states of the virtual photon while superscripts include the nucleon polarization component and/or a prime for beam polarization, as appropriate. Rosenbluth separation of the combinations \( \nu_T R_{LT} + \nu_{TT} R_{TT} = \nu_L R_L + \nu_T R_T \) requires variation of the beam energy, which was not performed in this experiment. The cm phase space is given by \( \nu_0 = k/q_0 \), where \( k \) and \( q_0 \) are the pion and equivalent real photon momenta, while the kinematical factors \( \nu_T = 1, \nu_{TT} = \epsilon, \nu'_{TT} = \sqrt{1-\epsilon^2}, \nu_L = \epsilon S, \nu_{LT} = \sqrt{2}\epsilon S(1+\epsilon), \nu'_{LT} = \sqrt{2}\epsilon S(1-\epsilon) \) are elements of the virtual photon density matrix based upon the transverse and scalar longitudinal polarizations, \( \epsilon = (1+2q_0^2Q^2/2)^{-1} \) and \( \epsilon S = q^2/2Q^2 \). Finally, \( \phi \) is the angle between the scattering and reaction planes.

The experiment was performed in Hall A of Jefferson Lab using standard equipment described in Ref. \([14]\). A beam of 4531 ± 1 MeV electrons, with current ranging between about 40 and 110 \( \mu \)A, was rastered on a 15 cm LH2 target. The beam polarization, averaging 72% for the first two running periods and 65% for the third, was measured nearly continuously using a Compton po-
larimeter, with systematic uncertainties estimated to be about 1% [15].

Scattered electrons and protons were detected in two high-resolution spectrometers, each equipped with a pair of vertical drift chambers for tracking and a pair of scintillation planes for triggering. Protons were selected using the correlation between velocity and energy deposition in plastic scintillators and pion production was defined by cuts on missing mass and the correlation between missing energy and missing momentum. The proton polarization was analyzed by a focal-plane polarimeter (FPP). Detailed descriptions of the FPP and its calibration procedures can be found in Refs. [16, 17]. The electron spectrometer remained fixed at 14.1° with a central momentum of 3.66 GeV/c, while the proton spectrometer angle and momentum were adjusted to cover the angular distribution. Although the motion of the spectrometers was limited to the horizontal plane, the boost from cm to lab focuses the reaction into a cone with an opening angle of only 13° and provides enough out-of-plane acceptance to access all of the response functions, even those that vanish for coplanar kinematics. Cross sections were deduced by comparison with a Monte Carlo model of the phase space and acceptance for each setting, including radiative corrections. This model reproduces the observed distributions very well [15].

The nucleon polarization at the target in the cm frame was deduced from the azimuthal distribution for scattering in the FPP using the method of maximum likelihood. The likelihood function takes the form

\[
\mathcal{L} = \prod_{\text{events}} \frac{1}{2\pi} (1 + \xi + \eta \cdot R)
\]

where \(\xi\) represents the false (instrumental) asymmetry, \(R\) is a vector containing the response functions, and \(\eta\) is a vector of eventwise calculable coefficients that depend upon kinematical variables, differential cross section, beam polarization and helicity, FPP scattering angles and analyzing power, and spin transport matrix elements. The system of equations derived from \(\partial \ln \mathcal{L} / \partial R_m = 0\) is solved using an iterative procedure. The procedure was tested using pseudodata: a model was used to compute response functions for each accepted event, the predicted polarization was transported to the focal plane using the same transport matrix as for the data analysis, and the azimuthal angle in the FPP was sampled according to its probability distribution. The pseudodata were then analyzed in the same manner as real data. We found that the model responses are recovered with fluctuations consistent with the statistical uncertainties. We also found that small deviations between acceptance-averaged and nominal \(Q^2\) can be compensated using a dipole form factor.

Systematic uncertainties due to acceptance normalization, FPP analyzing power, beam polarization, elastic subtraction, false asymmetry, and spin rotation matrix elements were evaluated by comparing results from replays differing by a perturbation of the relevant parameter. The propagation of systematic uncertainties for fitted Legendre coefficients or multipole amplitudes was evaluated using fits to those data sets. Data for \(W = 1.23\) GeV at \(Q^2 = 1.0\) (GeV/c)² are shown in Fig. 11 for bin widths of \(\Delta W = \pm 0.01\) GeV and \(\Delta Q^2 = \pm 0.2\) (GeV/c)². We show \(R_{LT}, R_{LT}^T, R_{LT}, R_{LT}^T\), and \(R_{TT}^T\) extracted from the \(\phi\) dependence of \(\tilde{\sigma}\) with error bars from fitting; the large error bars or missing bins for \(\cos \theta \sim 0\) reflect inadequate \(\phi\) coverage for this separation, but the phenomenological analyses use the actual differential cross sections. The bins of \(\cos \theta\) for polarization were chosen to give approximately uniform statistics. Inner error bars with endcaps show statistical uncertainties and outer error bars without endcaps include systematic uncertainties. The systematic uncertainties in response functions and derived quantities are typically small compared with statistical or fitting uncertainties.

Figure 1 also shows predictions from several recent models: MAID2003 [3, 19], DMT [21, 22], SAID [22, 23], and SL [24]. Although the first three response functions in column 1 and the last in column 3 have been observed before, the other 12 response functions have been observed here for the first time. The first two columns are determined by real parts of interference products and tend to be dominated by resonant amplitudes, while the last two columns are determined by imaginary parts that are more sensitive to nonresonant amplitudes. Thus, one finds relatively little variation among models for the first two columns and much larger variations for the last two, but none provides a uniformly good fit, especially to imaginary responses.

Having factorized out leading dependencies on \(\sin \theta\), the response functions should be polynomials in \(\cos \theta\) of relatively low order, especially if the assumption of \(M_{1+}\) dominance is valid near the \(\Delta\) resonance. However, good fits over a range of \(W\) require additional terms in \(R_{LT}, R_{LT}^T, R_{LT}, R_{LT}^T\), and \(R_{TT}^T\). The green dashed curves fit coefficients of Legendre expansions to the data for each response function independently, including terms beyond \(M_{1+}\) dominance as needed; the extra terms have negligible effect upon the SMR and EMR values obtained using the traditional truncation formulas. Our results for the Legendre analysis are compared with those of Joo et al. [25] for CLAS data in the top section of Table I. These Legendre results for EMR overlap, but our result for SMR is more precise and significantly smaller.

The solid red curves in Fig. 11 show a multipole analysis that varies the real and imaginary parts of all s-wave and p-wave amplitudes, except \(\text{Im}M_{1-}\), plus real parts of 2− multipoles. Higher partial waves were determined using a baseline model, here based upon Born terms for pseudovector coupling. We did not vary \(\text{Im}M_{1-}\) because all models considered predict that it is negligible for our \(W\) range, yet experimentally it is strongly correlated with
FIG. 1: (Color online) Data for response functions at $W = 1.23$ GeV and $Q^2 = 1.0$ (GeV/$c^2$) are compared with recent models and with fits. The labeling distinguishes L, T, LT, and TT contributions to the unpolarized (0) cross section and to transverse (t), normal (n), or longitudinal (l) components of recoil polarization with an h to indicate helicity dependence, if any. Linear combinations that cannot be resolved without Rosenbluth separation are identified by L+T. Black dash-dotted, dotted, short-dashed, and long-dashed curves represent the MAID2003, DMT, SAID and SL models, respectively. The green mid-dashed curves show a Legendre fit while the solid red curves show a multipole fit.

$\text{Im} S_{1-}$. Note that we could not achieve acceptable multipole fits without varying the $s$-wave amplitudes with respect to baseline models and we found that the imaginary part of $S_{0+}$ is especially important. Small improvements for some of the responses can be obtained by varying other $d$-wave amplitudes also, but the uncertainties in the quadrupole ratios increase because higher partial waves are not strongly constrained by these data and correlations between parameters become more severe. Fits starting from the MAID2003, DMT, or SL models are practically indistinguishable from those shown, but SAID is less suitable as a baseline model because some of its $\ell_\pi = 2$ amplitudes are too large. The insensitivity of quadrupole ratios to the choice of baseline model is shown in Table II. Therefore, the multipole analysis provides nearly model-independent quadrupole ratios; we choose as final the results based upon the Born baseline to minimize residual theoretical bias.

Both Legendre and multipole analyses reproduce the data well but the multipole analysis is more fundamental, employs fewer parameters (16 vs. 50), and uses the data for all response functions simultaneously while the more phenomenological Legendre analysis fits each response function independently and ignores the relationships between Legendre coefficients required by expansions of those coefficients in terms of products of multipole amplitudes. A more detailed paper is forthcoming that shows that neither assumption of the traditional Legendre analysis ($s$ truncation and $M_{1+}$ dominance) is sufficiently accurate for data with the present levels of completeness and precision. The relative error in the traditional Legendre analysis is particularly severe for EMR.

Recent data on quadrupole ratios for $Q^2 < 1.6$ (GeV/$c^2$) are compared with representative models in Fig. 2. Note that the MAID2003, DMT, and SL models included previous EMR and SMR data in their parameter optimization. The present result for EMR disagrees strongly with the SAID prediction and is nearly identical to the data for $Q^2 = 0$, suggesting that EMR is nearly constant over this range. Unlike the somewhat smaller CLAS results for EMR, our multipole result does not depend upon $s$ truncation or $M_{1+}$ dominance. Similarly, our SMR result is close to those for $Q^2 < 0.2$ (GeV/$c^2$), suggesting that SMR is nearly constant over this range also. The stronger $Q^2$ dependence of lattice QCD calculations may arise because the quenched approximation misses pionic contributions that are expected to be important at low $Q^2$.

In summary, we have measured angular distributions of 14 separated response functions plus 2 Rosenbluth combinations for the $p(\vec{e}, e'\vec{p})\pi^0$ reaction at $Q^2 = 1.0$ (GeV/$c^2$) across the $\Delta$ resonance, of which 12 have been obtained for the first time. Dynamical models describe responses governed by real parts of interference products relatively well, but differ both from each other and from the data more strongly for imaginary parts that are more sensi-
gives distinctly smaller quadrupole ratios, demonstrating traditional Legendre analysis also fits the data well but and systematic errors; where available, outer error bars with- reduce clutter. Inner error bars with endcaps show statisti- TABLE I: Quadrupole ratios for DMT, SAID and SL, respectively. Magenta bars show lattice dash-dotted, and cyan dotted curves represent MAID2003, LEGS, filled triangles, MIT, cross, ELSA; open circles, CLAS. Small horizontal displacements are used to reduce clutter. Inner error bars with endcaps include model error. Red, green dashed, blue circles, CLAS; filled triangles, MIT; cross, ELSA; open squares, MAMI; open triangle, ELSA. FIG. 2: (Color online) Red circles, present results from mul- tipole analysis; open squares, MAMI; open triangle, LEGS; filled triangles, MIT; cross, ELSA; open circles, CLAS. Small horizontal displacements are used to reduce clutter. Inner error bars with endcaps show statistical and systematic errors; where available, outer error bars without endcaps include model error. Red, green dashed, blue dash-dotted, and cyan dotted curves represent MAID2003, DMT, SAID and SL, respectively. Magenta bars show lattice QCD results.

| method/baseline | SMR, % | EMR, % | \(\chi^2\) |
|-----------------|--------|--------|-----------|
| Legendre        | -6.11 ± 0.11 | -1.92 ± 0.14 | 1.50      |
| Joo et al.      | -7.4 ± 0.4 | -1.8 ± 0.4 |           |
| Born            | -6.84 ± 0.15 | -2.91 ± 0.19 | 1.85      |
| MAID2003        | -6.90 ± 0.15 | -2.79 ± 0.19 | 1.67      |
| DMT             | -6.82 ± 0.15 | -2.70 ± 0.19 | 1.67      |
| SL              | -6.79 ± 0.15 | -2.81 ± 0.19 | 1.64      |
| SAID            | -7.38 ± 0.15 | -2.53 ± 0.20 | 1.85      |

*Weighted average of CLAS data for \(Q^2 = 0.9 \text{ (GeV/c)}^2\) from [27].

tive to nonresonant mechanisms. None of the theoretical models considered provides a uniformly good description of the polarization data. We performed a nearly model-independent multipole analysis and obtained SMR = \(-(6.84 \pm 0.15)\)% and EMR = \(-(2.91 \pm 0.19)\)%.

that its assumptions about the relative magnitudes and phases of multipoles are not sufficiently accurate. A more detailed presentation of the fitted multipole amplitudes will be given in a longer paper.

This work was supported by DOE contract No. DE-AC05-84ER40150 Modification No. M175 under which the Southeastern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility. We acknowledge additional grants from the U.S. DOE and NSF, the Canadian NSERC, the Italian INFN, the French CNRS and CEA, and the Swedish VR.

[1] N. Isgur, G. Karl, and R. Koniuk, Phys. Rev. D 25, 2394 (1982).
[2] A. J. Buchmann and E. M. Henley, Phys. Rev. C 63, 015202 (2000).
[3] M. Fiolhais, G. Golli, and S. Sirca, Phys. Lett. B373, 229 (1996).
[4] S. S. Kamalov and S. N. Yang, Phys. Rev. Lett. 83, 4494 (1999).
[5] C. Alexandrou et al., Phys. Rev. Lett. 94, 021601 (2005).
[6] D. Drechsel et al., www.kph.uni-mainz.de/maid/maid2003
[7] J. J. Kelly et al., to be submitted to PRC (unpublished).
[8] G. A. Warren et al., Phys. Rev. C 58, 3722 (1998).
[9] T. Pospischil et al., Eur. Phys. J. A 12, 125 (2001).
[10] P. Bartsch et al., Phys. Rev. Lett. 88, 142001 (2002).
[11] K. Joo et al., Phys. Rev. C 68, 032201 (2003).
[12] C. Kunz et al., Phys. Lett. B564, 21 (2003).
[13] A. S. Raskin and T. W. Donnelly, Ann. Phys. (N.Y.) 191, 78 (1989).
[14] J. Alcorn et al., Nucl. Instrum. Meth. A522, 294 (2004).
[15] S. Escoffier, Ph.D. thesis, University of Paris, 2001.
[16] R. E. Roché, Ph.D. thesis, Florida State University, 2003.
[17] V. Punjabi et al., Phys. Rev. C 71, 052205 (2002).
[18] Z. Chai, Ph.D. thesis, Massachusetts Institute of Technology, 2003.
[19] D. Drechsel et al., Nucl. Phys. A645, 145 (1999).
[20] D. Drechsel et al., www.kph.uni-mainz.de/maid/dmt
[21] S. S. Kamalov et al., Phys. Rev. C 64, 032201(R) (2001).
[22] R. A. Arndt et al., gwadacs.gwu.edu
[23] R. A. Arndt et al., in Proceedings of the Workshop on the Physics of Excited Nucleons (NSTAR2002), edited by S. A. Dytyman and E. S. Swanson (World Scientific, Singapore, 2003).
[24] T. Sato and T.-S. H. Lee, Phys. Rev. C 63, 055201 (2001).
[25] K. Joo et al., Phys. Rev. Lett. 88, 122001 (2002).
[26] R. Beck et al., Phys. Rev. C 61, 035204 (2000).
[27] G. Blanpied et al., Phys. Rev. Lett. 79, 4337 (1997).
[28] N. F. Sparveris et al., Phys. Rev. Lett. 94, 022003 (2005).
[29] F. Kalleicher et al., Zeit. Phys. A 359, 201 (1997).