Relativistic Effects and Two-Body Currents in ^{2}H$(\vec{e}, e'p)n$ Using Out-of-Plane Detection

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Measurements of the ^{2}H$(\vec{e}, e'p)n$ reaction were performed with the out-of-plane magnetic spectrometers (OOPS) at the MIT-Bates Linear Accelerator. The longitudinal-transverse, f_{LT} and f'_{LT}, and the transverse-transverse, f_{TT}, interference responses at a missing momentum of 210 MeV/c were simultaneously extracted in the dip region at $Q^2 = 0.15$ (GeV/c)^2. In comparison to models of deuteron electrodisintegration, the data clearly reveal strong effects of relativity and final-state interactions and the importance of two-body meson-exchange currents and isobar configurations. We demonstrate that such effects can be disentangled by extracting these responses using the novel out-of-plane technique.

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Careful studies of the deuteron are fundamental to nuclear physics. Because of its relatively simple structure, reliable calculations can be performed in both nonrelativistic and relativistic models [1–6] for a given nucleon-nucleon (*NN*) potential, making the deuteron a primary testing ground for any realistic nuclear model. The electromagnetic probe is of particular importance because it is well understood and weak enough to allow a simple perturbative interpretation of the observables in terms of charge and current matrix elements. For these reasons, the electrodisintegration of the deuteron provides precise information on both the ground-state wave function [7–10] and the electromagnetic currents arising from meson-exchange (MEC) and isobar configurations (IC) [11,12]. As the deuteron is often used as a neutron target, such detailed understanding of both its structure and currents, as well as the dynamics of final-state interactions (FSI), is crucial for applications such as the extraction of precise information on the neutron electromagnetic form factors [13–16]. While in the past the study of realistic *NN* potentials has been the main point of interest, the roles of MEC and IC, and the question of relativistic corrections (RC), have come into focus recently.

Stringent constraints on nuclear models can be provided through measurements of the individual interference responses in the electron-deuteron scattering [1,3,4]. The reason for this is that small but dynamically interesting amplitudes can be considerably amplified by interference with dominant amplitudes and thus may become accessible. For example, the longitudinal-transverse response f_{LT} is particularly sensitive to the inclusion of relativistic effects [17], while the so-called fifth response f'_{LT} arises purely through final-state interactions [18]. The transverse-transverse response f_{TT} appears to be mostly sensitive to MEC and IC [19], and this sensitivity increases as the kinematics are moved away from the quasielastic (QE) ridge. By properly choosing kinematical regimes and performing systematic studies of these three responses, the role played by various interaction effects can be disentangled [12].

However, very few data on f'_{LT} and f_{TT} exist [18–20]. This is due to the fact that they require the detection of protons out of the electron scattering plane which became possible only recently. A limited set of data on the cross-section asymmetry, A_{LT}, or f_{LT} [17,21–25] is available mainly in QE kinematics and in the region of low missing momentum. The data were obtained with sequential measurements left and right of the momentum transfer, which may be vulnerable to systematic errors in aspects such as luminosity variations and kinematic phase-space matching when forming A_{LT} or extracting f_{LT}. Obtaining precise and consistent data on all three response functions is therefore desirable, in particular in the region of high missing momenta where the sensitivity to the various currents and dynamical effects is large. This is precisely the aim of the unique out-of-plane spectrometer facility (OOPS) at the MIT-Bates Linear Accelerator. Recently, we exploited this novel technique of performing precise extractions of the interference responses by simultaneous and symmetric measurements about the direction of the momentum transfer. This method minimizes possible systematic uncertainties in the extraction. Furthermore, we made simultaneous measurements of these interference response functions over a wide kinematical region, especially where the effects to be studied are enhanced.

In the one-photon exchange approximation, the cross section for the ${}^2\mathrm{H}(\vec{e},e'p)n$ reaction with an unpolarized target can be written with five independent terms as a function of the energy and momentum transfer (ω, q) and the polar and azimuthal angles of knocked-out protons with respect to the momentum transfer direction in the center-of-mass frame of the np pair $(\theta_{pq}^{\mathrm{cm}}, \phi_{pq}^{\mathrm{cm}})$ [26]:

$$\begin{aligned}\frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} = c[&\rho_L f_L + \rho_T f_T + \rho_{LT} f_{LT}\cos(\phi_{pq}^{\mathrm{cm}}) \\ &+ \rho_{TT} f_{TT}\cos(2\phi_{pq}^{\mathrm{cm}}) \\ &+ h\rho'_{LT} f'_{LT}\sin(\phi_{pq}^{\mathrm{cm}})]. \end{aligned} \tag{1}$$

Here c is proportional to the Mott cross section, h is the helicity (± 1) of the incident electrons, ρ are the virtual-photon density matrix elements which depend only on the electron kinematics, and f are the response functions in the center-of-mass system as functions of ω, q, and $\theta_{pq}^{\mathrm{cm}}$. In "parallel" kinematics where $\theta_{pq}^{\mathrm{cm}} = 0$, the interference response functions (f_{LT}, f'_{LT}, and f_{TT}) vanish. The angle $\theta_{pq}^{\mathrm{cm}}$ is directly related to the missing momentum, $\vec{p}_m$, which is the difference between $\vec{q}$ and the ejected proton momentum. In the plane-wave impulse approximation, $\vec{p}_m$ is equal to the initial proton momentum in the deuteron.

By measuring the differential cross sections at fixed values of ω, q, and $\theta_{pq}^{\mathrm{cm}}$, but at angles $\phi_{pq}^{\mathrm{cm}} = 0°, 90°$ (and/or 270°), and 180° around the $\vec{q}$ vector, one can form various asymmetries:

$$A_{LT} = \frac{\sigma_{0°} - \sigma_{180°}}{\sigma_{0°} + \sigma_{180°}} = \frac{\rho_{LT} f_{LT}}{\rho_L f_L + \rho_T f_T + \rho_{TT} f_{TT}}, \tag{2}$$

$$A'_{LT} = \frac{\sigma_{90°}^{(+1)} - \sigma_{90°}^{(-1)}}{\sigma_{90°}^{(+1)} + \sigma_{90°}^{(-1)}} = \frac{\rho'_{LT} f'_{LT}}{\rho_L f_L + \rho_T f_T - \rho_{TT} f_{TT}}, \tag{3}$$

$$A_{TT} = \frac{\sigma_{0°} + \sigma_{180°} - 2\sigma_{90°}}{\sigma_{0°} + \sigma_{180°} + 2\sigma_{90°}} = \frac{\rho_{TT} f_{TT}}{\rho_L f_L + \rho_T f_T}, \tag{4}$$

and extract the interference responses to study the contributions of each individual term to the cross section:

$$f_{LT} = [\sigma_{\phi=0°} - \sigma_{180°}](2c\rho_{LT})^{-1}, \tag{5}$$

$$f'_{LT} = [\sigma_{90°}^{(h=+1)} - \sigma_{90°}^{(h=-1)}](2c\rho'_{LT})^{-1}, \tag{6}$$

$$f_{TT} = [\sigma_{0°} + \sigma_{180°} - 2\sigma_{90°}](4c\rho_{TT})^{-1}. \tag{7}$$

The experiment was carried out with the OOPS system [27] used to detect knockout protons in coincidence with electrons detected in the reconfigured one-hundred-inch proton spectrometer (OHIPS) [28]. We developed a detailed computer-aided alignment method which ensured a precise alignment of the OOPS with absolute accuracies in position and angles better than 0.3 mm and 0.3 mrad, respectively [29]. Spectrometer optics data were obtained for all OOPS modules and OHIPS. We performed ${}^1\mathrm{H}(e,e'p)$ coincidence studies between OHIPS and the OOPS, and extracted absolute cross sections which were within 2% of the expected values [30,31]. Calculations of the coincidence phase space, the effect of the radiative tail, and multiple scattering corrections were carried out by Monte Carlo simulations [32].

The measurements of the ${}^2\mathrm{H}(\vec{e},e'p)n$ reaction were performed by using an 800-MeV, 1% duty-factor polarized electron beam with an average current of 4 μA and a 160-mg/cm^2 thick liquid deuterium target. The polarization of the electron beam was measured with the B-line Møller polarimeter [33] and averaged to be 38.6 ± 4.0%. The OHIPS was positioned at a scattering angle of $\theta_e = 31.0°$ and its central momentum was set to 645.0 MeV/c, corresponding to $q = 414$ MeV/c, $\omega = 155$ MeV, and $x_{\mathrm{Bjorken}} = 0.52$. Three OOPS were positioned at $\phi_{pq}^{\mathrm{cm}} = 0°$, 90°, and 180° with $\theta_{pq}^{\mathrm{cm}}$ fixed at 38.5°, thus providing simultaneous measurements of all three interference responses f_{LT}, f'_{LT}, and f_{TT} as well as their associated asymmetries at $p_m = 210$ MeV/c [31]. In these kinematics the signal-to-noise ratio in the most forward OOPS was about 1:1. Here we report on the results from the measurements in the "dip" region between the QE ridge ($\omega \simeq 90$ MeV, $x_{\mathrm{Bjorken}} \simeq 1$) and the Δ resonance. Measurements of the f_{LT} and f'_{LT} response functions on top of the QE ridge were also performed [34] and will be reported on later.

In order to suppress possible systematic uncertainties in extracting the data and to reduce the effects of kinematic broadening when comparing to calculations, only events from the overlapping portion of the detector acceptances are selected after matching the $\phi_{pq}^{\mathrm{cm}} = 0°$ and 180° detector phase spaces. Figure 1 shows the asymmetry A_{LT} as a function of p_m. The PWBA (plane-wave Born approximation)+RC result of Ritz *et al.* [1] is compared to the full relativistic calculations (PWBA) by Hummel and Tjon [3] and the σ_{cc1} prescription of de Forest [35], which used an analytic formalism to extrapolate the off-shell electron-proton cross section and hence to give an effective relativistic expansion in terms of p_m/m_p (m_p − mass of the proton) in the current operator. It

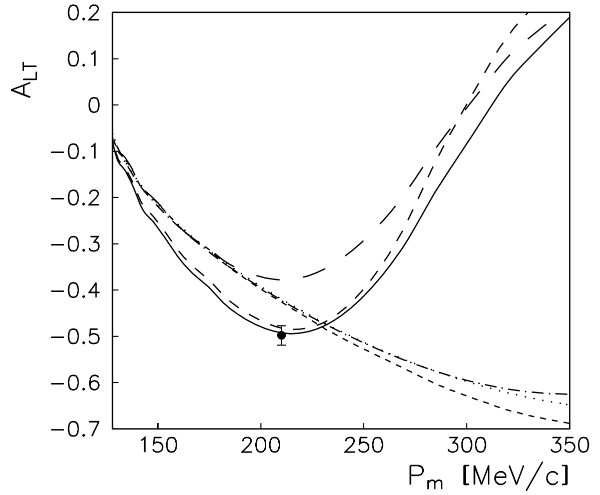

FIG. 1. The asymmetry A_{LT} as a function of p_m. The calculations by Ritz *et al.* [1]: PWBA+RC (short-dashed line), PWBA+FSI+RC (dashed line), PWBA+FSI+MEC+IC (long-dashed line), and full − PWBA+FSI+MEC+IC+RC (solid line); Hummel and Tjon [3]: PWBA (dash-dotted line); σ_{cc1} [35] (dotted line).

seems that all these plane-wave approaches do not differ much and they obviously fail to describe the data.

The results show that the asymmetry is strongly sensitive to final-state interactions. The calculations with simple plane-wave approximations are inadequate, and consequently a rigorous effort in including FSI is needed. Also, relativistic current operators or relativistic corrections are necessary. The Bonn potential of the *NN* interactions [36] is used in the calculations of Ritz *et al.*, but the predictions show little sensitivity to the choice of other realistic *NN* potentials for these kinematics [1]. In addition, the calculations show very little sensitivity to the two-body currents for A_{LT}.

The out-of-plane detection also makes it possible to measure the helicity asymmetries A'_{LT}, which represent the imaginary part of the interference of the longitudinal and transverse current matrix elements. Figure 2 shows A'_{LT} for the OOPS at $\phi_{pq}^{\mathrm{cm}} = 90°$. The calculations by Ritz *et al.* [1] agree well with the data when the FSI are included, because A'_{LT} arises entirely from complex amplitudes interfering in the final-state processes. In PWBA, where only real amplitudes are involved, the asymmetry vanishes. In addition, as indicated by Eq. (1), when $\phi_{pq}^{\mathrm{cm}} = 0°$ or $180°$, A'_{LT} vanishes. As a consistency check, our data in the two in-plane OOPS together yielded an asymmetry of 0.006 ± 0.009.

It is interesting to observe that the asymmetries are opposite in sign to the p-shell proton knockout of the $^{12}\mathrm{C}(\vec{e}, e'p)^{11}\mathrm{B}$ reaction [28,37], as shown by both data and calculations. In the low missing momentum region of the deuteron electrodisintegration, the FSI is dominated by the spin-spin interactions of the *np* pair, while in the p-$^{11}\mathrm{B}$ interactions, the spin-orbit parts are more important.

The determination of the absolute cross section makes it possible to extract also individual response functions.

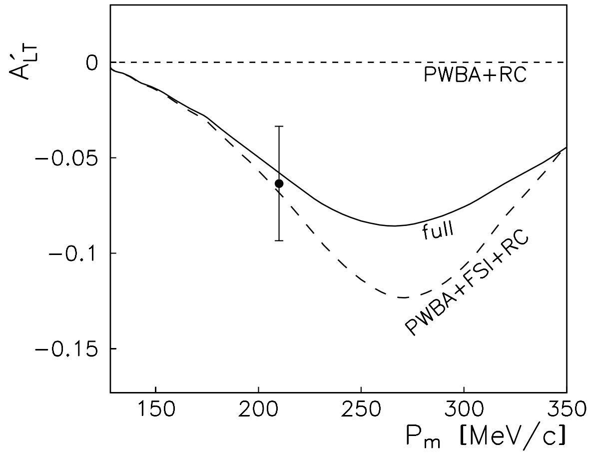

FIG. 2. The asymmetry A'_{LT} as a function of p_m. Calculations by Ritz *et al.* [1] with ingredients as labeled.

In asymmetries, the denominators may cancel some of the effects in the numerators, as can be seen in our f_{LT} data shown in Fig. 3. Here the data are again compared to calculations by Ritz *et al.* [1]. Not only relativistic corrections and detailed calculations of FSI, but also the two-body currents, are needed in order to bring the predictions into agreement with the data. However, one observes substantial cancellations between the effects of two-body currents and FSI. Accordingly, the calculations by Hummel and Tjon [3] which include only limited contributions from FSI, but do not contain two-body currents, are also in agreement with the data.

Isolating the contributions of the two-body currents from other competing reaction effects can be done by separating the remaining interference response, f_{TT}. As shown in Fig. 4, various models predict that f_{TT} (or A_{TT}) is strongly sensitive to the two-body currents while they do not depend so much on the relativistic effects, in contrast to A_{LT}

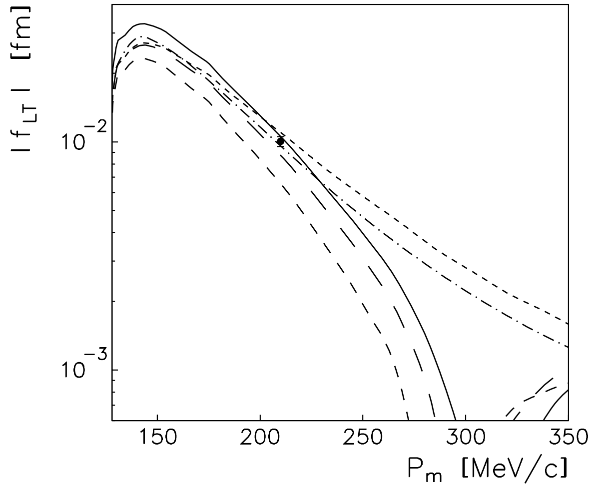

FIG. 3. The response function f_{LT} as a function of p_m. The calculations by Ritz *et al.* [1]: PWBA (short-dashed line), PWBA+FSI (dashed line), PWBA+FSI+MEC+IC (long-dashed line), and full (solid line), while by Hummel and Tjon [3]: PWBA+FSI (dash-dotted line).

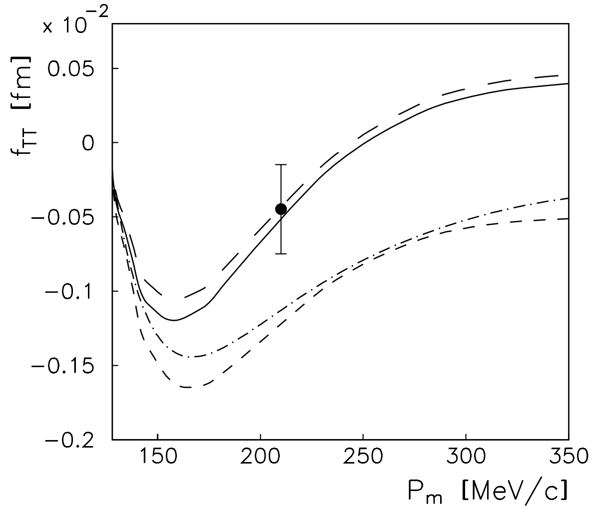

FIG. 4. The response function f_{TT} as a function of p_m. The calculations by Ritz *et al.* [1]: PWBA+FSI+RC (dashed line), PWBA+FSI+MEC+IC (long-dashed line), and full (solid line), and by Hummel and Tjon [3]: PWBA+FSI (dash-dotted line).

and f_{LT}. Our data agree with the full calculations by Ritz *et al.* [1] which have recently been improved by including retardation diagrams. The calculations by Hummel and Tjon [3] which currently do not contain two-body contributions, fail to describe the data. The f_{TT} data demonstrate the power of using out-of-plane detection and new observables to isolate such small, but interesting, contributions to the electromagnetic currents in deuteron disintegration.

In summary, our data clearly reveal strong effects of relativity and FSI, as well as of two-body currents arising from MEC and IC. We conclude that the two-body currents and relativity are extremely important to the understanding of the deuteron, and thus, more rigorous relativistic calculations including all ingredients discussed here are needed. We demonstrate that these competing effects in the deuteron electrodisintegration can be disentangled and studied by extracting interference response functions using the novel out-of-plane technique. Obviously, additional precise data are needed which can now be obtained easily by using the fully commissioned OOPS system.

Out-of-plane measurements with higher statistical precision have been planned in the near future, especially in the region of higher missing momentum ($>$250 MeV/c) and as a function of the energy transfer up to the Δ resonance [38]. These data will clarify the role of relativity and two-body currents, and provide a detailed understanding of the isobar configurations and possible knowledge of the Δ-N interactions. The figure of merit in measuring A'_{LT} will be improved by an order of magnitude when a highly polarized continuous-wave beam is used and two OOPS are mounted simultaneously at $\phi_{pq}^{\mathrm{cm}} = \pm 90°$.

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[1] F. Ritz, H. Göller, Th. Wilbois, and H. Arenhövel, Phys. Rev. C **55**, 2214 (1997).
[2] B. Mosconi and P. Ricci, Nucl. Phys. **A517**, 483 (1990); B. Mosconi, J. Pauschenwein, and P. Ricci, Phys. Rev. C **48**, 332 (1993).
[3] E. Hummel and J. A. Tjon, Phys. Rev. C **42**, 423 (1990); **49**, 21 (1994).
[4] S. Jeschonnek and T. W. Donnelly, Phys. Rev. C **57**, 2438 (1998).
[5] J. W. Van Orden, N. Devine, and F. Gross, Phys. Rev. Lett. **75**, 4369 (1995).
[6] J. L. Forest *et al.,* Phys. Rev. C **54**, 646 (1996).
[7] M. Bernheim *et al.,* Nucl. Phys. **A365**, 349 (1981).
[8] S. Turck-Chieze *et al.,* Phys. Lett. B **142**, 145 (1984).
[9] K. I. Blomqvist *et al.,* Phys. Lett. B **424**, 33 (1998).
[10] Z.-L. Zhou *et al.,* Phys. Rev. Lett. **82**, 687 (1999).
[11] H. Arenhövel, Nucl. Phys. **A384**, 287 (1982).
[12] S. Gilad, W. Bertozzi, and Z.-L. Zhou, Nucl. Phys. **A631**, 276c (1998).
[13] E. E. W. Bruins *et al.,* Phys. Rev. Lett. **75**, 21 (1995).
[14] I. Passchier *et al.,* Phys. Rev. Lett. **82**, 4988 (1999).
[15] M. Ostrick *et al.,* Phys. Rev. Lett. **83**, 276 (1999).
[16] H. Zhu *et al.,* Phys. Rev. Lett. **87**, 081801 (2001).
[17] M. van der Schaar *et al.,* Phys. Rev. Lett. **68**, 776 (1992).
[18] S. M. Dolfini *et al.,* Phys. Rev. C **51**, 3479 (1995); **60**, 064622 (1999).
[19] A. Pellegrino *et al.,* Phys. Rev. Lett. **78**, 4011 (1997).
[20] T. Tamae *et al.,* Phys. Rev. Lett. **59**, 2919 (1987).
[21] J. Ducret *et al.,* Phys. Rev. C **49**, 1783 (1994).
[22] D. Jordan *et al.,* Phys. Rev. Lett. **76**, 1579 (1996).
[23] F. Frommberger *et al.,* Phys. Lett. B **339**, 17 (1994).
[24] H. J. Bulten *et al.,* Phys. Rev. Lett. **74**, 4775 (1995).
[25] W. Kasdorp *et al.,* Phys. Lett. B **393**, 42 (1997).
[26] W. Fabian and H. Arenhövel, Nucl. Phys. **A314**, 253 (1979).
[27] S. M. Dolfini *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **344**, 571 (1994); J. Mandeville *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **344**, 583 (1994).
[28] X. Jiang, Ph.D. thesis, University of Massachusetts−Amherst, 1998 (unpublished).
[29] J. Comfort *et al.,* "Precision Alignment of The OOPS," Bates internal report, 1998 (to be published).
[30] S.-B. Soong, Ph.D. thesis, MIT, 1998 (unpublished).
[31] J. Chen, Ph.D. thesis, MIT, 1999 (unpublished).
[32] C. Vellidis, "Manual of AEEXB," Bates internal report, 1997; J. Templon *et al.,* Phys. Rev. C **61**, 014607 (2000).
[33] J. Arrington *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **311**, 39 (1992).
[34] Z.-L. Zhou *et al.,* in *Proceedings of the 2nd Workshop on Electronuclear Physics with Internal Targets and the BLAST Detector,* edited by R. Alarcon and R. Milner (World Scientific, Singapore, 1999), p. 278.
[35] T. de Forest, Jr., Nucl. Phys. **A392**, 232 (1983).
[36] R. Machleidt *et al.,* Phys. Rep. **149**, 1 (1987).
[37] J. Mandeville *et al.,* Phys. Rev. Lett. **72**, 3325 (1994).
[38] W. Bertozzi *et al.,* Update to Bates Proposal 89-14, 1997.