A Measurement of the Interference Structure Function, $R_{LT}$, for the $^{12}C(e, e'p)$ reaction in the Quasielastic Region.

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The coincidence cross-section and the interference structure function, $R_{LT}$, were measured for the $^{12}C(e, e'p)^{11}B$ reaction at quasielastic kinematics and central momentum transfer of $|\vec{q}| = 400$ MeV/c. The measurement was at an opening angle of $\theta_{pq} = 11^\circ$, covering a range in missing energy of $E_m = 0$ to 65 MeV. The $R_{LT}$ structure function is found to be consistent with zero for $E_m > 50$ MeV, confirming an earlier study which indicated that $R_L$ vanishes in this region. The integrated strengths of the p- and s-shell are compared with a Distorted Wave Impulse Approximation calculation. The s-shell strength and shape are compared with a Hartree Fock-Random Phase Approximation calculation. The DWIA calculation overestimates the cross sections for p- and s-shell proton knockout as expected, but surprisingly agrees with the extracted $R_{LT}$ value for both shells. The HF-RPA calculation describes the data more consistently, which may be due to the inclusion of 2-body currents in this calculation.

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I. INTRODUCTION

The coincidence $(e, e'p)$ reaction in the quasielastic region ($\omega \approx Q^2/2M_p$) has long been recognized as an ideal tool to study the single particle wave-functions of the proton in the nucleus, and such experiments have resulted in quantitative tests of the nuclear mean field theory [1]. Until recently, most experiments only measured cross-sections. This experiment also extracts one of the structure functions. The separation of structure functions provides additional information about the electron scattering process. These structure functions are sensitive to specific aspects of the reaction mechanism or to properties of the target nucleus (final state interactions, meson exchange currents, multi-body effect, wave function, nucleon form factors...), and their measurement will be crucial for the understanding of these detailed aspects of the electron scattering process [2] [3].

The quasielastic cross-section was originally attributed entirely to single particle knockout [4], but more recent experiments suggest that a considerable amount of strength comes from two-body and possible multi-body processes [5,6]. Evidence for multinucleon processes is also seen in $(e, e'p)$ experiments on carbon in the dip and delta kinematic regions [7–10]. These studies show that there is more strength at large missing energies than is expected from a one-body process, and that the transverse part of the cross-section is enhanced compared to the longitudinal part. A similar result is seen in an L/T separation for the $^3He(e, e'p)$ reaction [11]. An experiment on $^{16}O$ for p-shell knockout showed an enhancement of the $R_{LT}$ structure function [12]. These anomalies have not been explained by either final state interactions or meson exchange currents. A number of previous $R_{LT}$ measurements were performed on deuterium [13–16] where multi-body processes do not play a role. The measurement reported here is aimed at providing further information regarding the character of this excess strength through the isolation of the $R_{LT}$ response function. The kinematics for the extraction of $R_{LT}$ were chosen to be similar to ref [5], where a signature of the anomalous strength has already been observed in a separation of $R_L$ and $R_T$.

In the one-photon exchange approximation, the interaction of the electron with the target nucleus can be described by the exchange of a single virtual photon having a four-momentum $q_\mu = (\omega, \vec{q})$. The spin averaged cross-section for the $(e, e'p)$ reaction can then be expressed as [17]:

\[ \sigma_{ee'}(\omega, q) = \frac{1}{2} \int \frac{d^2 \vec{k}}{(2\pi)^2} \frac{d^2 \vec{k'}}{(2\pi)^2} \frac{d\Omega}{4\pi} \frac{d\Omega'}{4\pi} \rho_{ee'}(\vec{k}, \vec{k'}, \omega, \vec{q}) \]
\[ \frac{d^5\sigma}{dE_f d\Omega_e d\Omega_p} = \frac{1}{(2\pi)^3} C_{\text{kin}} \sigma_M f^{-1}_{\text{rec}} \times \begin{cases} v_L R_L + v_R R_R + v_{LT} R_{LT} \cos(2\phi_{pq}) + v_{LT} R_{LT} \cos(\phi_{pq}) \\ v_{LT} R_{LT} \cos(\phi_{pq}) \end{cases} \] (1.1)

where the \(v_{\alpha\beta}\) terms represent the lepton tensor elements which depend only on the electron vertex, and the \(R_{\alpha\beta}\) terms represent the nuclear response functions. The indices denote longitudinal (\(L\)) or transverse (\(T\)) polarization of the virtual photon with respect to the momentum transfer direction. Furthermore, \(\phi_{pq}\) is the angle between the electron scattering plane (containing the incoming and scattered electron momentum vectors) and the reaction plane (containing the momentum transfer \(\vec{q}\) and outgoing proton momentum vectors.) \(\sigma_M\) is the Mott cross-section, \(f_{\text{rec}} = |1 + (\omega p_p - E_p q \cos(\theta_{pq}))/M_p|\) is the recoil function and \(C_{\text{kin}} = M_{\text{rec}} M_p p_p / M_A\) is a kinematic factor [18], where \(M_{\text{rec}}\) is the recoil mass, \(E_p, p_p\) and \(M_p\) are the proton energy, momentum and mass respectively. The momentum and energy transfer are given by \(q\) and \(\omega\) respectively, and \(\theta_{pq}\) is the angle between the momentum transfer and the outgoing proton. For \(\phi_{pq} = 0\) and \(\pi\), the proton is said to be emitted “in plane”. To separate the various structure functions, several measurements are needed at the same \(q\) and \(\omega\). The \(R_L\) and \(R_T\) structure functions can be separated by a Rosenbluth separation. The \(R_{LT}\) structure function can be separated by an out of plane measurement, and the \(R_{LT}\) structure function can be separated by measuring the cross-section at both sides of the \(q\) vector (\(\phi_{pq} = 0\) and \(\phi_{pq} = \pi\)) leaving all other kinematic variables the same [19]. \(R_{LT}\) is then determined from:

\[ R_{LT} = \frac{1}{2v_{LT}} \frac{(2\pi)^3}{C_{\text{kin}} \sigma_M f_{\text{rec}}} \times \begin{cases} \frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} & \left(\frac{\phi_{pq} = 0}{\phi_{pq} = \pi}\right) \\ \frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} & \left(\frac{\phi_{pq} = \pi}{\phi_{pq} = 0}\right) \end{cases} \] (1.2)

The kinematics of in-plane coincidence scattering allows for only four independent scalar variables. This set of variables can be chosen to be \(\{q, \omega, E_p, \theta_{pq}\}\) or \(\{q, \omega, E_m, P_m\}\) (among other possibilities.) The variable \(\theta_{pq}\), therefore, is not independent from the missing energy \((E_m = \omega - T_p - T_R)\) and the missing momentum \((P_m = \vec{p}_p - \vec{q}) = \sqrt{p_p^2 + q^2 - 2p_p q \cos(\theta_{pq})}\). Thus the range in missing momentum that is sampled in the measurement depends directly on the range of the opening angle, \(\theta_{pq}\).

II. THE EXPERIMENT AND ANALYSIS

The experiment was performed in the North Hall of the MIT-Bates linear electron accelerator facility. The electron beam energy was 576.0±0.9 MeV at an average current of about 3 \(\mu\)A and a 1% duty factor. The target was a 208.9 \(mg/cm^2\) thick carbon film. The electrons were detected at 44° using the high resolution (\(\Delta p/p \approx 10^{-4}\)) energy loss spectrometer system [20] (ELSSY) in coincidence with in-plane protons detected by a prototype “out-of-plane spectrometer” (OOPS) [21–26]. These settings correspond to quasielastic kinematics with a central momentum transfer of \(q = 404\) MeV/c and energy transfer of \(\omega = 112\) MeV. The protons were detected at two successive settings of 42.9° and 64.7° (on the opposing side of the beam line from the electron spectrometer) corresponding to opening angles of \(\theta_{pq} = 10.2°\) (\(\phi_{pq} = 0°\)) and \(\theta_{pq} = 11.7°\) (\(\phi_{pq} = 180°\)) respectively. The maximum opening angle was limited by geometric constraints of the North Hall. A slight mismatch of \(\theta_{pq}\) between the two settings was caused by an initial ambiguity in the beam energy. This was fully resolved after the experiment and accounted for in the data analysis. Data were collected for proton momenta from 326 MeV/c to 462 MeV/c by stepping through four sets of central momenta for the OOPS at each of the two angular settings. This yielded data with a missing energy range covering both p- and s-shell proton knockout \((E_m = 0 to 65\) MeV\) from the carbon nucleus.

In order to make a meaningful extraction of \(R_{LT}\) using equation 1.2, all four independent kinematic variables for \(\phi_{pq} = 0°\) and \(\phi_{pq} = 180°\) data must be identical. This subtraction of the two measurements is complicated by the finite acceptance of the spectrometers. To maximize the accuracy of the extraction the data were completely analyzed in two dimensions, using bins of missing momentum vs. missing energy. The experimental cross-section for each bin \(B(E_m, P_m)\) is then given by:

\[ \left\langle \frac{d^6\sigma}{dE_f dE_m d\Omega_e d\Omega_p} \right\rangle_B = \sum_r n_r V_r (E_m, P_m) \] (2.1)

The summation is over all runs that have data contributing to bin \(B(E_m, P_m)\). \(N_r(E_m, P_m)\) is the number of counts contributing to this bin for run \(r\), and \(n_r\) is the normalization for that run (see below). \(V_r\) is the phase-space volume defined by:

\[ V_r (E_m, P_m)_B = \int_{B} \varepsilon_A dE_f dE_m d\Omega_e d\Omega_p \] (2.2)

where \(\varepsilon_A\) is the six dimensional efficiency of the spectrometers (from a Monte Carlo simulation) to detect particles contributing to a bin \(B(E_m, P_m)\) and the integration is over the acceptance of the spectrometers. A two dimensional contour plot (figure 1) of this volume for each of the two data sets reveals the complicated nature of the acceptance and the need for a mask to enforce overlap of the two data sets. This mask is chosen so that the phase-space volume for each of the two settings is large enough to expect a reasonable number of counts in the \((E_m, P_m)\) bins inside the masked region. The phase-space volumes are normalized for each run by a factor given by:
The data were corrected by the measured efficiencies of the spectrometers, which is incorporated into the factor \( n_r \) of formula 2.1. The integrated spectrometer efficiency was determined by measuring the elastic \(^1\)H(\(e, e'p\)) cross-section and comparing it with the values predicted by the Mainz [27] parametrization of the proton form factors [25,26]. The integrated spectrometer efficiency was found to be 98.4 ± 0.2%. The integrated efficiency of the proton spectrometer was determined by \(^1\)H(\(e, e'\)) scattering, and was found to be 96.3 ± 1.0% after all known detector dead times (4% to 6%) were taken into account [25,13,26]. The data were also corrected for radiative processes in a two dimensional manner using the code RADC [28], which unfolds the radiative tails in the missing momentum versus missing energy histogram using a formalism based on that of Mo and Tsai [29–32]. These corrections were typically around 22% for internal bremsstrahlung (Schwinger correction [33]) and small (2% to 3%) for all other processes. After this correction the \( R_{LT} \) response was calculated for each bin, and the resulting histograms were projected onto the missing energy axis for interpretation. Projection onto the missing momentum axis was not fruitful due to the sparsity of the data, so only one integrated data point could be obtained in the \( P_m \) dimension.

### III. RESULTS AND DISCUSSION

Figure 2 shows the histograms of the cross-section results for \( \phi_{pq} = 0^\circ \) and \( \phi_{pq} = 180^\circ \), along with the extracted \( R_{LT} \) values. The data clearly exhibit the p-shell proton knockout region from about 13 MeV to 28 MeV which is known to contain several excited states of the \(^{11}\)B residual nucleus [34]. The resolution in this experiment was not high enough to distinguish these states, although there is some indication of a peak corresponding to an excited state at about 24 MeV in missing energy (8 MeV excitation) [9].

The integrated cross-sections over the entire p-shell region are 8.3 ± 0.2 ± 0.1 nbarn/(MeV sr\(^2\)) for \( \phi_{pq} = 0^\circ \) (\( \theta_p = 42.9^\circ \)) and 13.1 ± 0.3 ± 0.3 nbarn/(MeV sr\(^2\)) for \( \phi_{pq} = 180^\circ \) (\( \theta_p = 64.7^\circ \)). The s-shell region ranges from 28 MeV up to 50 MeV in missing energy. This upper limit was established by a previous experiment separating \( R_L \) and \( R_T \) [5,35] where it was found that \( R_L \) vanishes formissing energies larger than 50 MeV.\(^a\)

The integrated cross-sections for the s-shell region are 3.5 ± 0.2 ± 0.1 nbarn/(MeV sr\(^2\)) for \( \phi_{pq} = 0^\circ \) (\( \theta_p = 42.9^\circ \)) and 5.9 ± 0.2 ± 0.1 nbarn/(MeV sr\(^2\)) for \( \phi_{pq} = 180^\circ \) (\( \theta_p = 64.7^\circ \)). The integrated cross-sections for the region above the s-shell, from 50 MeV to 75 MeV, are 0.8 ± 0.3 nbarn/(MeV sr\(^2\)) for \( \phi_{pq} = 0^\circ \) and 1.7 ± 0.4 nbarn/(MeV sr\(^2\)) for \( \phi_{pq} = 180^\circ \).

For extraction of \( R_{LT} \), the data were masked (see figure 1) before the \( R_{LT} \) calculation and subsequent projection onto the missing energy axis. The resulting histogram of \( R_{LT} \) (figure 2) clearly shows the p-shell and s-shell regions with strengths of 25 ± 2. ± 2 fm\(^3\) and 14 ± 2. ± 1 fm\(^3\) respectively. The \( R_{LT} \) strength is consistent with zero for missing energies larger than 50 MeV, which is consistent with the findings of ref. [5,35] that \( R_L \) is zero for missing energies larger than 50 MeV.

The experimental results are compared with non-relativistic distorted wave impulse approximation (DWIA) calculations [36,37] in figure 3. These calculations use a Wood-Saxon potential well to calculate the bound state wave functions, and an optical potential model to calculate the distortion of the outgoing protons. The parametrizations of the optical potentials used were due to Comfort et al. [38] (dashed lines), Jackson et al. [39] (dotted lines) and Schwandt et al. [40] (dot-dash lines). Plane wave impulse approximation (PWIA) calculations (solid lines) are also shown for comparison. A discussion of these optical potentials can be found in ref. [41].

There are significant discrepancies between the DWIA calculations and the data for both the p- and s-shell cross-sections. These discrepancies can be expressed as spectroscopic factors, which are defined as the ratio of the experimental cross-sections to the theoretical cross-sections assuming one proton per shell. The nominal value for the p-shell (s-shell) spectroscopic factor would thus be 4 (2), however it has been well documented that these factors are closer to 2.5 and 0.9 for experimental data. [3] Taking the averaged result of the cross-sections calculated using the three different optical potentials, the spectroscopic factors for the p-shell are 1.93 ± 0.07 at \( \phi_{pq} = 0^\circ \) and 2.40 ± 0.14 at \( \phi_{pq} = 180^\circ \), and for the s-shell 0.67 ± 0.09 at \( \phi_{pq} = 0^\circ \) and 0.82 ± 0.08 at \( \phi_{pq} = 180^\circ \). The uncertainties quoted include the full experimental uncertainties and estimated theoretical uncertainties equal to the standard deviations of the theoretical predictions added in quadrature. These spectroscopic values fall well below the expected values of 4 and 2, but are consistent with previous experiments which have found spectral functions in the range of 2 to 3 for the p-shell and 0.6 to 1.2 for the s-shell [42].

An extension of the spectroscopic factor can be constructed by comparing the results of the extracted \( R_{LT} \) value with the theoretical \( R_{LT} \) predictions. This comparison results in \( R_{LT} \)-spectroscopic factors of 4.6 ± 1.1 for the p-shell and 1.4 ± 0.3 for the s-shell. This is in surprisingly good agreement with the nominal values of 4 and 2. Since \( R_{LT} \) is the difference of the \( \phi_{pq} = 0^\circ \) and \( \phi_{pq} = 180^\circ \) cross-sections, it should be expected to scale with the same spectroscopic factors as the full cross-sections. This discrepancy indicates that DWIA calculations are not sufficiently accurate to predict the
separated $R_{LT}$ structure function. A similar conclusion was reached by Spaltedt et al. [12] who found that the $R_{LT}$ spectroscopic factor for p-shell proton knockout from $^{16}O$ in quasielastic kinematics was enhanced as compared to the $R_L$ and $R_T$ spectroscopic factors.

An additional, more complete calculation was performed for the s-shell region by J. Ryckebusch in the framework of a self consistent Hartree-Fock Random Phase Approximation (HF-RPA) [43,46]. This calculation included two body currents related to meson exchange currents and $\Delta(1232)$ excitation. They also included two nucleon knockout contributions to the cross-section. For the distribution of the s-shell strength in missing energy, a Lorentzian curve was used:

$$S_{1/2}^t (E_m) = \frac{1}{\pi} \frac{W (E_m - \varepsilon_F)}{(E_m - \varepsilon_F - |\varepsilon_h - \varepsilon_F|)^2 + [W (E_m - \varepsilon_F)]^2}$$

which includes an energy-dependent width as prescribed by Mahaux [47]:

$$W (E) = \frac{9E^4}{E^4 + (13.27)^4} [MeV]$$

which was obtained from a compilation of experimental data [48]. Furthermore $\varepsilon_h$ is the energy needed to remove a proton from the s-shell and $\varepsilon_F$ is the Fermi energy ($\varepsilon_F \approx 18 MeV$, $|\varepsilon_h - \varepsilon_F| \approx 23 MeV$, for a $^{12}C1s_1/2$ proton).

The cross-section versus missing energy is then given by

$$\sigma_{1S_{1/2}}^t (E_m) = 0.3 \cdot S_{1/2}^t (E_m) \sigma_{1S_{1/2}}^{HF-RPA}$$

which includes a reduction factor of 0.3. This factor is similar to a spectroscopic factor, but is smaller on account of the lack of an absorptive imaginery potential in the treatment of the final state interactions in the HF-RPA calculation [44] [45]. The same factor was used for both the cross-sections and the extracted $R_{LT}$ structure function. The resulting curves in figure 4 show a good agreement between theory and data in the s-shell region. This indicates that more complete calculations are needed to predict the $R_{LT}$ structure functions and that the Mahaux shape models the s-shell distribution well. This better agreement might be due to the sensitivity of the $R_{LT}$ structure function to two body currents in the nucleus, as suggested by ref. [49]. Figure 4 also shows the contribution of two nucleon knockout to the cross-section. This contribution is too small to explain the difference between the two calculations. Also note that since this data was taken at an electron scattering angle of 44° the virtual photon was mostly longitudinally polarized and therefore little strength is expected in the continuum ($E_m > 50 MeV$), based on the findings of refs. [5,35].

A different picture is obtained when the same calculation is compared to $R_L$ and $R_T$ structure functions separated by Ulmer et al. [5]. These quasi-elastic data were taken in parallel kinematics ($\theta_{pq} = 0$) at an energy transfer $\omega = 122 MeV$ and a momentum transfer $q = 397 MeV/c$. The calculation was scaled by a factor of 0.4 to fit the $R_L$ data (instead of the 0.3 used above). As can be seen in figure 5, the shape of $R_L$ for the s-shell data is correctly described by the calculation, but for $R_T$ the calculation underestimates the data. Also the continuum strength for $R_T$ is significantly under predicted by this calculation. This discrepancy cannot be explained by the two body contributions to the cross-section or the two-nucleon knockout contribution (dashed line). We must conclude that even the HF-RPA calculations cannot describe the separated transverse response function consistently. The good description of the $R_{LT}$ data may be due to the combination of the longitudinal response going to zero (and therefore driving $R_{LT}$ to zero also) and the chosen longitudinal electron kinematics.

IV. SUMMARY

A first measurement of the $R_{LT}$ structure function for the carbon nucleus at quasi-elastic kinematics was performed. This measurement verifies that the s-shell strength vanishes for missing energies larger than 50 MeV. The strength of the $R_{LT}$ structure function cannot be correctly described by a DWIA calculation when using the same spectroscopic factors that are needed to predict the cross-sections. This discrepancy may be due to the sensitivity of $R_{LT}$ to the two body contributions to the nuclear current, as indicated by a more complete HF-RPA calculation, which successfully predicts $R_{LT}$ and $R_L$. However, these same calculations do not correctly replicate the measured $R_T$ structure function. Spectroscopic functions by Mahaux accurately describe the s-shell distributions in missing energy but they underestimate the strength in the continuum ($E_m > 50 MeV$). Additional measurements and better calculations are needed to fully understand the sensitivities of the $R_{LT}$ and other structure functions to the various components of the nuclear current. A consistent set of measurements that separate as many response functions as possible will go a long way towards the understanding of the nuclear current. A cluster of OOPS spectrometers is currently being used at the Bates accelerator laboratory to make such measurements [50].

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FIG. 1. Contour histogram of the summed acceptance volume \( \sum V_r(\varepsilon_m, P_m) \) for the \( \phi_{pq} = 0^\circ \) and \( \phi_{pq} = 180^\circ \) data, and the overlap (bold line) of the two regions that was used for the analysis of this data set (see text.)

FIG. 2. Cross-sections and extracted \( R_{LT} \) response functions versus missing energy. The data has been fully corrected for radiative effects and normalizations. Error bars include the statistical uncertainty only.
FIG. 3. Data compared with DWIA calculations [28,29]. The top row shows the results for the p-shell (13 MeV < $E_m$ < 28 MeV) for $\phi_{pq} = 0^\circ$, $\phi_{pq} = 180^\circ$ and $R_{LT}$, the bottom row shows the same for the s-shell (28 MeV < $E_m$ < 50 MeV). The various curves are for different optical potentials used for the final state proton distortions (see text.)
**FIG. 4.** Comparison of the s-shell data with an HF-RPA calculation [36] using a spectroscopic function to model the shape of the s-shell. The dotted line in the top two plots indicate the contribution from two-nucleon knockout.

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### Cross Section [nb/ (MeV $^2$ sr $^2$)]

- $\theta_{pq} = 12^\circ$, $\phi = 0^\circ$
- $\theta_{pq} = 12^\circ$, $\phi = 180^\circ$
- $\theta_{pq} = 11^\circ$, $\phi = 0^\circ$
- $\theta_{pq} = 11^\circ$, $\phi = 180^\circ$

**FIG. 5.** Comparison of the separated $R_L$ and $R_T$ structure functions from Ulmer et al. [4], with an HF-RPA calculation [36] using an s-shell spectroscopic function. The dashed line indicates the two-nucleon knockout contribution.

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