First Measurement of the Imaginary Part of the Transverse-Longitudinal Nuclear Response

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We have measured a new electron scattering observable, the "fifth" structure function, f'_{01}, which is the imaginary part of the transverse-longitudinal interference response. Its observation requires a longitudinally polarized beam and coincident, out-of-plane particle detection. f'_{01} arises from interference between reaction channels and provides an additional means for their disentanglement. In the quasielastic $^{12}\mathrm{C}(\vec{e},e'p)$ measurements reported here, f'_{01} is driven by the interference of the direct knockout and rescattering amplitudes.

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Electron scattering is a widely recognized precision probe of nuclear and nucleon structure [1–6]. The well-understood nature of the electromagnetic interaction, the ability of electrons to penetrate the nuclear interior, and the possibility of independent variation of energy and momentum transfer all contribute to the usefulness of the technique. In addition, modern electron accelerators can provide high quality beams with large currents and duty factors.

To take full advantage of the capabilities of electron scattering, especially for excitations in the nuclear continuum, exclusive measurements are required. In many cases, this implies coincident measurements of reaction products out of the scattering plane, the use of polarized targets, polarized beams, or focal plane polarimetry. With these techniques new observables can be measured which permit the isolation of important and otherwise inaccessible amplitudes [5,6]. In this Letter, we report the first measurement of a new structure function by means of coincident, out-of-plane electron scattering [7].

The $A(\vec{e},e'x)B$ cross section corresponding to the reaction depicted in Fig. 1 can be written in the one-photon exchange approximation as [5,8]

$$\begin{aligned} d\sigma_h &= d\sigma_{\mathrm{Mott}}(\rho_{00}f_{00} + \rho_{11}f_{11} + \rho_{01}f_{01}\cos\phi_{xq} \\ &\quad + \rho_{1-1}f_{1-1}\cos 2\phi_{xq} + h\rho'_{01}f'_{01}\sin\phi_{xq}) \qquad (1a) \\ &= \Sigma + h\Delta, \qquad (1b) \end{aligned}$$

where $d\sigma_{\mathrm{Mott}}$ is the cross section for scattering from a point charge, ϕ_{xq} is the azimuthal reaction angle for the emitted particle, ρ_{ij} is the lepton tensor whose components depend solely on the properties of the electron vertex, and $h = \pm 1$ is the electron helicity. The cross section is separated into helicity dependent and independent parts. All information pertaining to the scatterer is contained in the nuclear structure functions, f_{ij}, which are bilinear combinations of the transverse and longitudinal components of the nuclear current with respect to the direction of the momentum transfer (**q**). The indices i and j (-1, 0, or 1) denote the helicity components of the transition current. Each of the structure functions exhibits different degrees of sensitivity to the underlying details of the microscopic nuclear theory. Single-arm (e,e') measurements depend on the energy and angle integrated transverse (f_{11}) and longitudinal (f_{00}) structure functions. Coincident cross sections without electron or target polarization contain two additional structure func-

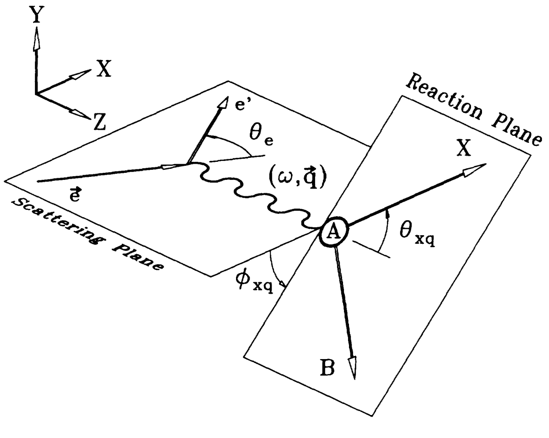

FIG. 1. Kinematic definitions for the $A(\vec{e},e'x)B$ reaction.

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tions (f_{1-1} and f_{01}), which can be separated by measurements at values of ϕ_{xq} on a cone centered on $\mathbf{q}$. A fifth structure function (f'_{01}) can be observed if the incident electrons are also longitudinally polarized.

This new observable, or "fifth" structure function, breaks the symmetry for decay particles scattering above and below the plane. The helicity dependent term in the cross section, Δ, which is proportional to f'_{01}, can be isolated with small systematic error through an asymmetry measurement:

$$A = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-}. \tag{2}$$

Note that $|A| \leq 1$, and that this asymmetry does not arise from a parity violating interaction as it would in the case of an $(\vec{e}, e')$ experiment. We have measured the fifth structure function asymmetry for both carbon [9] and deuterium [10]. The deuterium results will be reported in a separate paper.

The function f'_{01} is produced by the interference between two or more complex reaction amplitudes with different phases—a necessary condition for obtaining an imaginary component from the transverse-longitudinal response. In the quasielastic knockout kinematics of this experiment, the two dominant interfering amplitudes are those of the direct and rescattering processes. It is therefore not surprising that f'_{01} is highly sensitive to final state interactions (FSI) and vanishes [8,11] in the plane wave impulse approximation (PWIA), where the rescattering amplitude is ignored. The distorted wave impulse approximation (DWIA) based upon phenomenological optical potentials, which is the usual way of accounting for rescattering in all but the lightest nuclei, introduces uncertainties of the order of 10% in the cross section. Model uncertainties of this magnitude severely restrict the precision that can be obtained in measurements of absolute spectroscopic factors. The fifth structure function provides an observable for monitoring rescattering effects in knockout reactions and, therefore, it may permit much higher precision in nuclear structure studies.

Other cases where the fifth structure function may be used to isolate interfering amplitudes are the separation of resonant from competing channels in the study of nuclear [12] or nucleon [13] resonances. It has been suggested that f'_{01} may provide a key observable for the isolation of the resonant quadrupole excitation of the $\Delta^+(1232)$ from other "background" amplitudes. Experiments are being prepared both at Bates [13] and CEBAF which will attempt to perform this measurement.

The present $^{12}\mathrm{C}(\vec{e}, e'p)^{11}B$ measurements were performed at Bates in the North Experimental Hall with a 560 MeV electron beam having a duty factor of 0.6% and a polarization of (34±4)%. Data were acquired by using 200 and 600 mg/cm^2 targets, with quasielastic kinematics at a momentum transfer of 1.85 fm^{-1}, which implies an energy transfer of 70.3 MeV. The high resolution ELSSY spectrometer [14] detected electrons in the horizontal plane at an angle of 40° with respect to the beam. The recently constructed Out-Of-Plane Spectrometer (OOPS) [15,16] measured coincident protons at $\theta_{pq} = 21°$ and 29° with $\phi_{pq} = 90°$ (i.e., above $\mathbf{q}$, which was at 59.6° with respect to the beam). As a systematic error check, we also measured a deuterium asymmetry in parallel kinematics ($\theta_{pq} = 0°$), where the fifth structure function must vanish. The OOPS is shown oriented at $\theta_{pq} = 29°$ in Fig. 2.

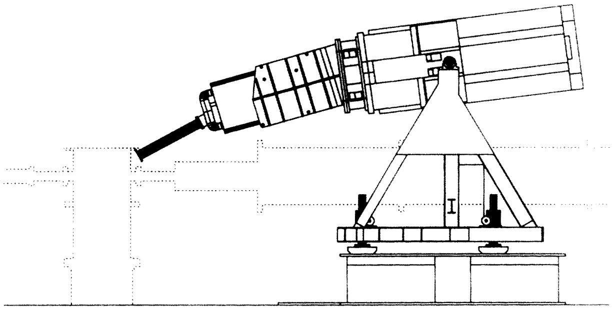

FIG. 2. The OOPS is shown at an angle of 29° above the scattering plane.

For each of the two out-of-plane points, approximately 0.2 C of electron charge were accumulated during 32 hours. The sign of the electron polarization was flipped with each beam pulse following a nearly random pattern generated by a 2^{64}-bit binary sequencer. By restricting the missing energy, we admitted only events corresponding to knockout of a p shell proton (15 MeV$< E_{\text{miss}} <$ 28 MeV). Substantially lower rates for the s shell did not allow the extraction of statistically significant results for this part of the missing energy spectrum.

The measured asymmetry, A, is insensitive to systematic uncertainties in the target thickness, charge collection, and all spectrometer efficiencies because these quantities cancel in the ratio. We also determined the fifth structure function by performing an absolute measurement of the helicity independent part of the cross section [Σ in Eq. (1b)],

$$f'_{01} = \frac{A\Sigma}{P\rho'_{01}\sigma_{\text{Mott}}} , \tag{3}$$

where P is the beam polarization.

Figure 3 compares the measured cross section, asymmetry, and structure function with theoretical calculations. The asymmetry data point at $\theta_{pq} = 0°$, which could be measured to high precision because of the large deuterium cross section, checks the systematic uncertainty. This point is consistent with zero, as it must be to maintain continuity. The two out-of-plane asymmetries are small compared to the causal limits (±1), but one expects them to be huge compared to the asymmetries observed in $(\vec{e}, e')$ experiments [17,18]. The uncertainties

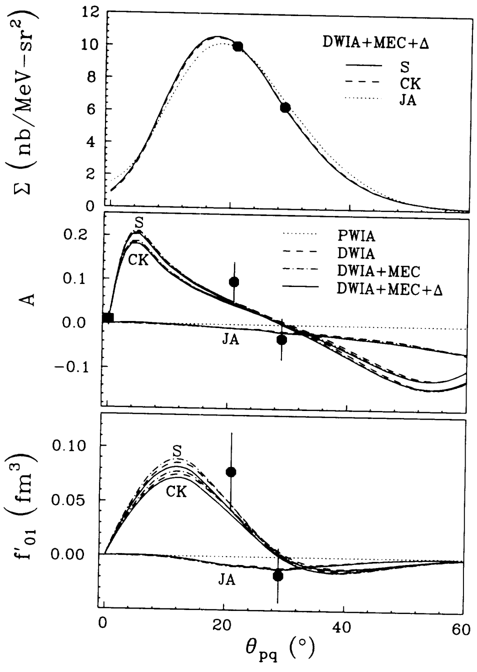

FIG. 3. The cross section, asymmetry, and fifth structure function are compared to theoretical predictions in the impulse approximation for three optical potentials. The square point at $\theta_{pq} = 0°$ in the asymmetry plot is a systematic uncertainty check based on measurements made with a deuterium target.

in the carbon measurements are dominated by counting statistics.

Theoretical calculations were performed in the framework of the Pavia group [5,19]. Both the knockout and the rescattering effects are calculated using a mean field optical model approach. The calculations labeled S use the optical potential of Schwandt *et al.* [20], CK indicates the potential of Comfort and Karp [21], and JA is the potential of Jackson and Abdul-Jalil [22]. The potential of Giannini and Ricco (GR) [23] was tested and found to closely follow S and CK. The cross section curves are corrected for meson exchange currents (MEC) and Δ-isobar configurations; these contributions are shown separately for A and f'_{01} and produce only small variations. All calculations have been corrected for Coulomb distortion of the incident electron in the effective momentum approximation [24]. The theoretical cross sections have been scaled to fit the data; the requisite scaling factors for S, CK, JA, and GR are 0.66, 0.67, 0.50, and 0.79, respectively. These same normalizations have also been applied to the fifth structure function calculations. The spectroscopic factor of 2.62±0.27 is consistent with earlier measurements of 2.48±0.39 at Bates [25], 2.26±0.23 at NIKHEF [26], and 2.5 at Saclay [27].

All of these potentials previously have been shown to provide reasonable descriptions of cross section data (e.g., see [26]). However, large differences in the asymmetry and structure function can be seen between JA and the other potentials. These differences are due to the relatively small real and imaginary central wells of JA. The observable f'_{01} demonstrates a degree of selectivity not seen in the cross section. The similar results produced by the other three optical models indicate that they are not only phase-shift equivalent for elastic electron scattering, but that they are also roughly equivalent for the construction of the entire $(e, e'p)$ scattering wave at these kinematics. More points with higher statistical precision are required to gauge the accuracy of the mean-field treatment of FSI.

In quasielastic knockout kinematics, the fifth structure function provides an observable, which is particularly useful for understanding the underlying dynamics of the rescattering process. This usefulness derives from the inherent accuracy of helicity asymmetry measurements and the fact that f'_{01} is sensitive to FSI in leading order and relatively insensitive to other corrections (e.g., MEC). One might expect the fifth structure function to provide information to guide theories that attempt to calculate scattering and rescattering effects consistently and beyond the phenomenological mean field, optical model approach (see, e.g., Ref. [28]).

The short running time that was required to obtain each reported data point indicates that substantially reduced uncertainty can be achieved for subsequent measurements with the same apparatus. Accelerator and detector developments will also improve future work. The storage ring at Bates is expected to increase the duty factor of the accelerator by nearly 2 orders of magnitude. The resulting improvement in the signal to background ratio will enable the use of higher beam currents and, consequently, allow the acquisition of more points with significantly higher statistical precision. The single OOPS spectrometer used in this measurement is the first element in a much more flexible, four-spectrometer OOPS system designed to measure all three interference structure functions [see Eq. (1a)] simultaneously. The supporting structure for the spectrometer cluster will provide a continuous range of out-of-plane angles.

The fifth structure function, the first observation of which is reported here, may prove to be useful in disentangling interfering processes. In quasielastic kinematics, it is an excellent tool for the study and separation of knockout and rescattering amplitudes. High precision data can be obtained with the asymmetry technique. The new generation of accelerators and detectors promises to provide information on this new observable for a variety of problems in nuclear and hadronic physics.

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