The quasielastic $^2\text{H}(e,e'p)n$ reaction at high recoil momenta

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The $^2\text{H}(e,e'p)n$ cross section was measured in Hall A of the Thomas Jefferson National Accelerator Facility (JLab) in quasielastic kinematics ($x = 0.96$) at a four-momentum transfer squared, $Q^2 = 0.67$ (GeV/c)$^2$. The experiment was performed in fixed electron kinematics for recoil momenta from zero to 550 MeV/c. Though the measured cross section deviates by $1 - 2\sigma$ from a state-of-the-art calculation at low recoil momenta, it agrees at high recoil momenta where final state interactions (FSI) are predicted to be large.

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The deuteron, as the only bound two-nucleon system, represents the simplest manifestation of the nuclear force and is therefore the natural starting point for investigation of the nature of the nuclear electromagnetic current. The applicability of reaction models for complex nuclei can be gauged by the success of these models in reproducing scattering observables on the deuteron. Further, by studying the deuteron in extreme kinematics where its short range structure is emphasized, one may determine to what extent its description in terms of nucleon/meson degrees of freedom must be supplemented by inclusion of explicit quark/gluon effects. This issue is of fundamental importance to nuclear physics. Finally, understanding the deuteron is required for the interpretation of a variety of experiments using the deuteron as an effective neutron target.

Coincidence $^2\text{H}(e,e'p)n$ reactions are particularly well suited to nucleon-nucleon (NN) interaction studies. Below pion threshold, the final state is completely specified. Further, by judicious choice of kinematics one can emphasize various aspects of the reaction dynamics [1]. Accessing the deuteron’s short range structure implies measurements at high recoil momentum, $p_r$ (i.e. the momentum of the undetected recoiling neutron). However, for certain kinematics, final state interactions (FSI) can change the cross section by an order of magnitude or more at high $p_r$ (see, e.g., Fig. 1 below). These large effects result from strength at low initial proton momentum feeding high $p_r$ due to np rescattering in the final state. Models which succeed under such stringent tests may then be applied with some confidence to infer aspects of the deuteron short distance structure in kinematics where $p_r$ is large but FSI are minimized. Such a situation is expected at large $x$ ($x = Q^2/2m\omega$) in “parallel kinematics”, where the proton is detected along the direction of $\vec{q}$ [2].

Although there is a substantial body of data on this reaction from facilities other than JLab, including unseparated cross sections [2, 3, 4, 5] as well as separations of response functions [6, 7, 8, 9, 10, 11, 12, 13, 14, 15], various limitations made it difficult to disentangle aspects of the reaction mechanism from the deuteron short range structure. For the cross section measurements, limitations in the accelerator energies available at Bates, Saclay, NIKHEF and Mainz frustrated such attempts by forcing measurement of very high recoil momenta to energy transfers far above the quasielastic peak. Thus, for the Turck-Chieze [2] and high $p_r$ Mainz data, the kinematics were in the $\Delta$-region where lack of knowledge of the reaction mechanism made it difficult to deduce aspects of the deuteron structure. Although the Mainz measurement sampled $p_r$ up to 928 MeV/c, the kinematics actually imply that the bulk of the cross section arises from interaction with the neutron, leaving the detected pro-
ton as a spectator. Further, since the kinematics were in the Δ-region of the inclusive \((e,e')\) spectrum, the inclusion of virtual nucleon excitations was required to obtain agreement with the data. Although the energy limitation is not shared by SLAC, the maximum current and duty factor restricted the range of recoil momenta there as well. In contrast, JLab’s combination of high beam energy, current and duty factor allows examining large recoil momenta at or even below quasielastic kinematics (i.e. \(x \geq 1\)), making the extraction of the deuteron structure less model-dependent.

The \(^2\)H\((e,e'p)n\) separation experiments have also been restricted in kinematical coverage for the reasons stated above. Nonetheless, they have revealed gaps in our understanding. Various calculations have difficulty reproducing both \(R_L\) and \(R_T\) \[1,11,12\]. The \(R_{LT}\) response and related \(A_{00}\) asymmetry \[1,11,12,13\] indicate the need for relativistic treatments but problems still exist in reproducing the data. For momentum transfers up to \(Q^2 \sim 1\) (GeV/c)\(^2\) a nonrelativistic calculation supplemented with the most important leading order relativistic contributions has been shown to agree quite well with a covariant approach \[16\]. More recent calculations of Jeschonnek, Donnelly and Van Orden \[17\] suggest that the bulk of the relativistic effects may be in the nucleon current operator, as opposed to the nuclear dynamics. They obtained good agreement between a manifestly covariant calculation involving the Gross equation \[15\] and a calculation using a nonrelativistic wave function and a relativistic nucleon current operator. In contrast, a calculation with a nonrelativistic wave function and current operator drastically failed to reproduce the results of the covariant calculation. These calculations highlight the importance of incorporating relativity properly. Also, if the relativistic effects are mostly in the current operator, they can be incorporated for heavier nuclei using the same approach. Due to its more tractable nature, the deuteron provides a testing ground for such an approach.

Our experiment (Experiment E94-004) consisted of measuring the unseparated cross section in quasielastic kinematics out to high \(p_r\). It was performed in Hall A of JLab using the high resolution spectrometer pair. A detailed description of the Hall A instrumentation is currently being prepared \[19\]. Electrons from the accelerator were incident on a 15 cm long liquid deuterium target. Scattered electrons and knockout protons were detected in the “left” (formerly “electron”) spectrometer and “right” (formerly “hadron”) spectrometer, respectively, each with nominally 6.0 mr collimators at their front ends. Each spectrometer was equipped with its standard detector package consisting of a pair of VDC’s for track reconstruction and a scintillator array for trigger definition. In addition, the electron spectrometer included an atmospheric pressure CO\(_2\) threshold Čerenkov detector for \(\pi^-/e\) discrimination.

Kinematics are given in Table I. The beam energy and electron spectrometer angle and central momentum were kept fixed throughout the experiment at incident and scattered energies of \(E = 3.110\) GeV and \(E' = 2.742\) GeV, respectively, and scattering angle of \(\theta_e = 16.06^\circ\), leading to central values of the four-momentum transfer squared of \(Q^2 = 0.665\) (GeV/c)\(^2\) and \(x = Q^2/2mu = 0.964\) (where \(\omega\) is the electron energy transfer and \(m\) is the proton mass). Listed below are the recoil momentum \(p_r\), the proton momentum \(p\), and the proton angle \(\theta_p\) relative to the beam direction. All quantities are expressed in the laboratory system. Also shown are the average luminosities corrected for estimated beam related target density changes.

| \(p_r\) MeV/c | \(p\) GeV/c | \(\theta_p\) deg | \(L_{avg}\) cm\(^{-2}\) s\(^{-1}\) |
|----------------|-------------|-----------------|----------------|
| 0              | 0.885       | -58.76          | 6.50E+37       |
| 100            | 0.874       | -65.22          | 2.16E+38       |
| 150            | 0.864       | -68.47          | 3.48E+38       |
| 200            | 0.851       | -71.73          | 3.59E+38       |
| 275            | 0.823       | -76.72          | 3.71E+38       |
| 300            | 0.812       | -78.41          | 3.76E+38       |
| 500            | 0.689       | -92.78          | 3.67E+38       |

Measurement of the elastic \(^1\)H\((e,e'p)\) reaction, taken with the spectrometers at the \(^2\)H\((e,e'p)n\) \(p_r = 0\) setting, served as a normalization check. The measured yield was compared to a simulation \[20\] using the Simon et al. \[21\] parameterization for \(G_{Me}\) and the \(G_{Ep}/G_{Me}\) ratio measured by Jones et al. \[22\]. The simulation included acceptance averaging as well as radiative folding \[23\]. In order to remove the ill-defined acceptance edges a technique involving “R-functions” was used \[24\]. Through the \(R\)-functions, a multi-dimensional contour in the space of the target variables and equidistant from a pre-defined boundary was defined and all events outside the contour were rejected. The same contour was used in the simulations and for the \(^1\)H\((e,e'p)\) and \(^2\)H\((e,e'p)n\) data. The ratio of integrated yield for the simulation to that for the \(^1\)H\((e,e'p)\) data was 1.054, amounting to a 5.4% correction for the \(^2\)H\((e,e'p)n\) data.

For the \(^2\)H\((e,e'p)n\) data, beam currents ranged from 10 \(\mu\)A to 100 \(\mu\)A. Since the electron kinematics were fixed, the electron arm served as a measure of the prod-

TABLE I: Kinematics (central values). The electron kinematics were fixed throughout the experiment with incident and scattered energies of \(E = 3.110\) GeV and \(E' = 2.742\) GeV, respectively, and scattering angle of \(\theta_e = 16.06^\circ\), leading to central values of the four-momentum transfer squared of \(Q^2 = 0.665\) (GeV/c)\(^2\) and \(x = Q^2/2mu = 0.964\) (where \(\omega\) is the electron energy transfer and \(m\) is the proton mass). Listed below are the recoil momentum \(p_r\), the proton momentum \(p\), and the proton angle \(\theta_p\) relative to the beam direction. All quantities are expressed in the laboratory system. Also shown are the average luminosities corrected for estimated beam related target density changes.
uct of electronic deadtime and target density; the electronic deadtime for the hadron arm was assumed to be negligible, since its trigger rate never exceeded 10 kHz. Computer deadtime was determined from the ratio of coincidence raw triggers to recorded events. In order to improve the reals-to-accidentals ratio, especially important at high $p_r$, a consistent vertex from both spectrometers was required and a cut on the missing mass was imposed. Finally, a cut on the summed analog signal from the Čerenkov detector was used to reduce the already small contamination from $\pi^-$ events in the electron arm.

The aperture/magnetic model of each spectrometer was tested by measuring a series of “white” spectra, scanned in overlapping momentum steps. The relative spectrometer acceptance was then extracted by an iterative procedure. For the $R$-function cuts described above, the results were in excellent agreement with the simulated phase space.

The total systematic uncertainty in the cross sections was estimated to be roughly 8%, nearly independent of $p_r$, except near zero where it grows sharply due to the shrinking of the phase space volume. The kinematic related uncertainties were estimated by computing the cross section at the center of a given bin in $p_r$, further weighted by $p_r^2$ to roughly account for the phase space volume, and then making variations of each kinematic quantity in turn. The quantities were varied in a correlated fashion, constrained by the elastic $^1\text{H}(e, e'p)$ kinematics and by independent measurement of the beam energy, obtained by measuring the position of the beam at a point of high dispersion in an eight dipole arc section. The quadrature sum of all kinematics related uncertainties was less than 2.5% for all recoil momenta not too close to zero. Other uncertainties were estimated to be: 2.0% (electronic deadtime $\times$ target density), 2.0% (electron arm solid angle; not accounted for in the $^1\text{H}(e, e'p)$ normalization where the acceptance was limited by the proton arm), 1.0% (beam charge relative to normalization), 3.0% (radiative correction) and 5.8% (normalization, consisting of 3.6% from uncertainty in the elastic form factors, 2.0% uncertainty from kinematics and 4.1% from other uncertainties specific to the normalization measurement). Adding these uncertainties quadratically yields a value of 7.2% taken to be independent of $p_r$.

The results for data along with various calculations are shown in Fig. 1. The top panel shows the radiatively corrected “reduced” cross section:

$$\sigma_{\text{red}} \equiv \frac{d^3\sigma}{d\Omega_e d\Omega_p} \times \frac{1}{f_{\text{rec}} K \sigma_{\text{CC1}}}$$

where $K$ is a kinematic factor, $\sigma_{\text{CC1}}$ is the half-off-shell electron proton cross section of de Forest [25] and $f_{\text{rec}}$ is a recoil factor which arises from the integration over missing mass. This division removes most of the kinematic dependence, except for the $p_r$ dependence, and results in a smooth spectrum vs. $p_r$. The bottom panel shows the relative deviation of data and theoretical predictions from the “full” calculation of Arenhövel [26] (described below). Also shown in the bottom panel is the systematic error band, arbitrarily placed vertically. The data were radiatively corrected by multiplying the measured cross section in each $p_r$ bin by the ratio of yield without and with radiative effects (internal and external), both estimated using Arenhövel’s full calculation. The calculation was radiatively folded using the model of Borie and Drechsel [27]. Both data and simulations were cut on the missing mass from $-3.5$ MeV to 10.5 MeV, resulting in a weak dependence on $p_r$ for the radiative correction factor. A straight-line fit to this dependence was used.

All of the models were acceptance averaged using MCLEEP [20]: the calculations of Arenhövel were performed on a grid over the experimental acceptance and interpolated for each event, whereas the calculations of Jeschonnek [17] were incorporated directly into the Monte Carlo simulation program as a subroutine pack-

![FIG. 1: Top panel: The reduced $^2\text{H}(e, e'p)n$ cross section for this experiment along with various model calculations (see the text for details). Bottom panel: Cross sections for data and calculations shown as percentage deviations from the “full” calculation of Arenhövel. Also shown is the systematic error band ($\pm 1\sigma$), arbitrarily placed on the vertical axis. This error band contains an overall 7.2% contribution added in quadrature with the kinematic contribution, the latter varying slightly with $p_r$.](image-url)
age. The Jeschonnek calculation was in the plane wave Born approximation (PWBA) and used a fully relativistic single-nucleon current operator with an alternate three-pole parameterization of the MMD nucleon form factors [29] and the Argonne V18 two-body interaction [30]. The calculations of Arenhövel included relativistic contributions of leading order in $p/m$ to the kinematic wave function boost and to the nucleon current. The Bonn $r$-space NN potential [31] and dipole nucleon form factors were used. The various curves are for PWBA, distorted wave Born approximation (DWBA, which includes FSI), and the “full” calculation which also includes non-nucleonic currents: meson exchange currents and virtual nucleonic excitations.

The two PWBA calculations are reasonably close to each other, but deviate at high $p_r$, presumably largely due to the different NN potentials employed. For $p_r > 300$ MeV/c the PWBA fails completely, whereas the full calculation including FSI and significant contributions from non-nucleonic degrees of freedom results in satisfactory agreement with the data. For $p_r < 100$ MeV/c the full theory deviates from the data by roughly $1\sigma$ growing to about $2\sigma$ at $p_r \sim 200 - 300$ MeV/c, adding statistical and systematic errors quadratically. It is important to resolve any possible discrepancies in this low $p_r$ region, especially in light of some of the neutron form factor measurements which exploit the deuteron in this kinematic region. Clearly, additional, higher precision measurements would be helpful in clarifying this situation. An experiment to systematically study this reaction over a broad kinematical range has already been proposed and conditionally approved by the JLab Program Advisory Committee [31]. This future experiment promises significantly smaller systematic errors, based on recently acquired experience with the experimental apparatus and on inclusion of a larger set of experimental cross checks and calibrations.

In summary, we have measured the $^2\text{H}(e,e'n)$ cross section at $Q^2 = 0.67$ (GeV/c)$^2$ and $x = 0.96$ for recoil momenta up to 550 MeV/c. The data indicate large FSI and substantial non-nucleonic effects at high $p_r$. The full calculation overestimates the cross section by $1 - 2\sigma$ at small recoil momenta.

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