RECENT EXPERIMENTS USING
POLARIZATION OBSERVABLES AT BATES
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ABSTRACT
In this talk I summarize the experiments completed at the MIT-Bates electron accelerator in the last few years and compare their results with those of recent experiments performed elsewhere that address the same or similar physics issues. The experiments described here focus on measurements of the nucleon form factors and studies of the three-body system in inclusive quasielastic electron scattering from polarized $^3$He.

1. Introduction

In the past few years several experiments using polarization observables to study the electromagnetic properties of hadrons and light nuclei have been completed at the MIT-Bates electron accelerator. The neutron magnetic form factor $G_M^n$ was obtained from two different experimental techniques, a measurement of the quasielastic asymmetry in inclusive scattering of polarized electrons from polarized $^3$He and a measurement of the $d(e, e'n)$ cross section.\(^2\) The neutron charge form factor $G_E^n$ was measured in the $d(Z, e's)$ spin-transfer reaction,\(^3\) demonstrating a promising new technique predicted to be insensitive to the theoretical uncertainties that have limited the accuracy of $G_E^d$ extracted from the deuteron unpolarized cross section.\(^4\) Studies of the deuteron ground state wave function and the reaction processes relevant to quasielastic scattering were made using the proton Focal Plane Polarimeter to measure the transferred polarization in the $d(Z, e'p)$ and $p(Z, e'p)$ reactions.\(^5\)

The quality of asymmetry measurements in the quasielastic $^3$He$(e, e')$ reaction has significantly improved over the first measurements.\(^6\) In a recent $^3$He$(e, e')$ experiment, the transverse-longitudinal asymmetry\(^7\) and the transverse asymmetry\(^1\) were measured at the top of the quasielastic peak, a region where corrections to plane wave impulse approximation (PWIA) calculations are expected to be minimized. In addition, the transverse-longitudinal asymmetry was measured on the low energy transfer side of the quasielastic peak where corrections from final state interactions are expected to be large.\(^8\) These data will help constrain the more realistic models currently being developed.

In this talk, the experiments recently completed at Bates are described and their results presented and compared with experiments performed at other laboratories which addressed similar physics issues. All experiments discussed here ran in the South Hall. Progress on the SAMPLE experiment is reported elsewhere in these
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2. Experimental Studies of the 3–Body System

It has been known for some time that quasielastic scattering of polarized electrons from polarized \(^3\)He can in principle be used to study the electromagnetic form factors of the neutron.\(^{10}\) The recent polarized \(^3\)He experiments have attained sufficient precision that theoretical uncertainties are now beginning to limit the accuracy of information about the neutron that can be obtained, so a better model of the \(^3\)He ground state wave function and the corrections from higher order reaction processes, such as final state interactions (FSI) and meson exchange currents (MEC), is needed. Although it has become apparent that at low \(Q^2\) inclusive scattering is less sensitive to the neutron charge form factor \(G_E^n\) than first estimated,\(^{11}\) inclusive spin-dependent scattering can yield information about \(G_M^n\), the reaction processes and the 3–body ground state.

For inclusive quasielastic scattering of longitudinally polarized electrons from a polarized spin–\(\frac{1}{2}\) target, the spin-dependent asymmetry can be written as a sum of two terms, \(A = \cos \theta^* A_T + \sin \theta^* \cos \phi^* A_{TL}\), where \(\theta^*\) and \(\phi^*\) are Euler angles defining the direction of the \(^3\)He spin relative to the momentum transfer \(q\). Through judicious choice of the target spin angle one can isolate either of the two asymmetry terms, which are sensitive to different spin-dependent response functions and, thus, to different nucleon form factors. For studies of the neutron, \(A_T\) is more sensitive to \(G_M^n\) and \(A_{TL}\) is more sensitive to \(G_E^n\).

Bates experiment 8802, which ran at Bates in Summer 1993, measured \(A_T\) and \(A_{TL}\) around the top of the quasielastic peak and \(A_{TL}\) on the low energy transfer side of the quasielastic peak. The experimental value of \(A_T\) was used to extract \(G_M^n\) from polarized \(^3\)He data for the first time. An optically-pumped polarized \(^3\)He target and 370 MeV longitudinally polarized electrons were used for the experiment. \(A_{TL}\) was measured with the electrons at a scattering angle of 70° \((Q^2 = 0.14 \text{ (GeV/c)}^2\) at the top of the quasielastic peak\) and \(A_T\) was measured at an electron scattering angle of -90° \((Q^2 = 0.20 \text{ (GeV/c)}^2\) at the top of the quasielastic peak\). The target spin was oriented at 42.5° to the incident beam direction. The results of each of these measurements are discussed below.

2.1. Inelastic \(A_{TL}\) at Low Energy Transfer

One kinematic region where measurements of the inclusive inelastic asymmetry could provide insight into the theoretical ingredients needed to accurately calculate spin-dependent quasielastic scattering is the wings of the quasielastic peak. On the low energy transfer side, the contribution to the asymmetry from the \(D\)–state component of the ground state wave function, which dominates the proton contribution to the spin-dependent properties, is enhanced relative to the top of the quasielastic peak; FSI are expected to be large because the final state nucleons have low kinetic
energy; and at inelastic kinematics near the elastic peak MEC might be important, as they appear to be needed to accurately describe the measured elastic form factors for tritium and $^3$He.$^{12}$

Data on $A_{TL}$ in the low energy transfer region of inelastic scattering were collected simultaneously with elastic scattering events. The kinematic region used for the inelastic asymmetry analysis extended from the three-body breakup threshold (energy transfer $\omega = 37.3$ MeV) to $\omega = 55.7$ MeV. The spectrometer resolution of 3.5 MeV FWHM did not allow separation of the 2- and 3-body breakup thresholds in this measurement. The measured elastic asymmetry $A_{el} = 29.9 \pm 3.9\%$ agrees well with the prediction of 32.1% calculated from fits to experimental data for the elastic form factors.$^{12}$

Fig. 1(a) shows the spectrometer yield both with and without $^3$He gas in the target. The elastic peak is seen clearly at low $\omega$ followed by the rise of the inelastic scattering events at higher $\omega$. To obtain the inelastic asymmetry, the measured asymmetries were normalized by the target and beam polarizations and corrected for the background from nontarget materials and for the asymmetry and yield from events in the elastic radiative tail. The details of the analysis are given elsewhere.$^8$

Fig. 1(b) shows the inelastic asymmetry in the low $\omega$ region, with the combined systematic and statistical errors, and the PWIA calculations of Schulze and Sauer$^{13}$ (solid) and Salmé et al.$^{14}$ (dashed). The experimental data agree surprisingly well with
Fig. 2. Measured values of $A_{T'}$ (left) and $A_{TL'}$ (right) around the top of the quasielastic peak and the PWIA predictions for the asymmetries. The theoretical curves for $A_{T'}$ are the same PWIA calculations as in Fig. 1(b). The band in the graph of $A_{TL'}$ indicates the spread in the results for reasonable ranges of various theoretical ingredients.

the PWIA calculations at all but the lowest energy transfer where the experimental asymmetry is larger than the prediction by approximately 3σ. More sophisticated calculations are currently in progress; S. Ishikawa and coworkers have formulated a model including FSI from which they calculate the inclusive asymmetry,\textsuperscript{15} and J. Carlson and coworkers are using a 3-body model which includes FSI and MEC to calculate the spin-dependent quasielastic response functions.\textsuperscript{16} The deviation from PWIA observed at the lowest $Q^2$ may indicate sizable FSI, which would be consistent with recently reported data from Bates of the unpolarized $e-^3$He cross section at the two- and three-body breakup thresholds,\textsuperscript{17} which found that the cross sections at threshold are in much better agreement with calculations including FSI than with PWIA predictions.

2.2. $A_{T'}$ and $A_{TL'}$ at Quasielastic Kinematics

Both $A_{T'}$ and $A_{TL'}$ were measured at kinematics centered around the top of the quasielastic peak using two spectrometers which operated asynchronously. For details on the analysis the reader is referred to the literature ($A_{T'}$, $A_{TL'}$). The results for $A_{T'}$ and $A_{TL'}$ are shown in Fig. 2. The measured values of $A_{T'}$ are in good agreement with the two PWIA calculations shown.\textsuperscript{13,14} The band in the PWIA predictions for $A_{TL'}$ was obtained by Titko and Donnelly\textsuperscript{7} by varying the nucleon form factors, NN potential and off-shell prescription used in the calculation. Each of these ingredients contribute roughly equally to the theoretical uncertainty. One can see from the data and the spread in the PWIA predictions that even without introducing higher order processes, the theoretical uncertainty in the PWIA calculations alone is significant at the relatively low $Q^2$ of this measurement, and the calculations indicated that it remains significant up to $Q^2 = 0.5$ (GeV/c)$^2$. $A_{TL'}$ differs by $1-2.5\sigma$ from PWIA predictions, possibly indicating that FSI or MEC effects are important. This is consistent
with the recently reported IUCF experiment CE25 measurement of the \( ^3\text{He}(p,pm) \) and \( ^3\text{He}(p,2p) \) target and beam analyzing powers and spin correlation functions.\textsuperscript{18} The \( ^3\text{He}(p,pm) \) target analyzing power was observed to deviate from PWIA quasielastic scattering predictions for \( q \lesssim 500 \text{ MeV/c} \), indicating that FSI effects are probably significant at low \( Q^2 \). The deviation of these experimental data from the PWIA is not in itself terribly interesting since higher order reaction processes such as FSI or MEC certainly must be present at some level. However, these data provide quantitative information about where the PWIA is a good description of quasielastic scattering that will help in the selection of kinematic regions which minimize theoretical uncertainties in \( G_E^n \) obtained from \( ^3\text{He} \) experiments.

3. The Electromagnetic Form Factors of the Neutron

Of all the nucleon form factors, the neutron charge form factor is the most difficult to measure at low \( Q^2 \) because the free neutron is unstable against beta decay and nuclear measurements are generally dominated by the protons because the physical neutron has zero net charge. However, measurements of spin-dependent observables in electron scattering from \(^2\text{H}\) and \(^3\text{He}\) can be significantly more sensitive to \( G_E^n \) than unpolarized measurements alone. In particular, the spin observables in exclusive quasielastic scattering from either \(^2\text{H}\) or \(^3\text{He}\) where the outgoing neutron is observed can be quite sensitive to \( G_E^n \).

The recent Bates experiment to measure \( G_E^n \) was a proof-of-principle of the technique of extracting this quantity from the spin transfer in the \( d(e',e'n) \) reaction.\textsuperscript{3} Although it provided no new data on \( G_E^n \), the experiment proved that the technique worked and achieved errors significantly better than the earliest experiments using inclusive quasielastic scattering with polarized \(^3\text{He}\) targets.\textsuperscript{6} Experiments of higher precision using this technique are planned at CEBAF. Elsewhere, a measurement recently made at the Mainz Mami microtron of the ratio of \( A_{TL} \) to \( A_{T'} \) in the exclusive quasielastic \( ^3\text{He}(e',e'n) \) reaction has shown that \( G_E^n \) can be extracted with very good precision using \(^3\text{He} \) targets also.\textsuperscript{19,20}

\( G_M^n \) was derived from the measured value of \( A_{T'} \) in the \( ^3\text{He}(e',e') \) experiment reported in the previous session. The value agrees with the dipole parameterization, with \( (G_M^n/\mu_n G_D)^2 = 0.998 \pm 0.117 \pm 0.059 \pm 0.030 \). Higher statistics measurements will be able to improve the quality of \( G_M^n \) measurements using this technique. An earlier experiment at Bates that extracted \( G_M^n \) from the \(^2\text{H}(e,e'n) \) quasielastic cross section\textsuperscript{2} reported values consistent with the dipole parameterization at \( Q^2 = 0.18 \) and 0.26 (GeV/c)\(^2 \) but found \( G_M^n \) to be significantly higher than the dipole form at \( Q^2 = 0.11 \) (GeV/c)\(^2 \). This data is in disagreement with more recent data from NIKHEF\textsuperscript{21} and Bonn\textsuperscript{22}, suggesting that systematic uncertainties are underestimated in at least one of the measurements.
The recent experiments show that measurements of spin observables can provide precise information about small quantities that are difficult to extract from unpolarized cross sections and that they can be successfully applied to measurements of the neutron form factors. Future experiments at Bates, Mainz, NIKHEF, and CEBAF will make use of these techniques for precision measurements of $G_M^n$ and $G_E^n$.

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5. References

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