Recent measurements with the out-of-plane spectrometer system at MIT-Bates

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Abstract. The recent experimental program with the out-of-plane spectrometer system (OOPS) at MIT-Bates encompassed an extensive set of d(\vec{e},e'p) measurements, investigations of the N\rightarrow\Delta transition using p(\vec{e},e'p)π^0 and p(\vec{e},e'π^+)n reaction channels, and studies of virtual Compton scattering (VCS) p(e,e'p)γ below the pion threshold. Preliminary results are presented.

Measurements of d(\vec{e},e'p) in the dip region

Early measurements of unpolarised responses for deuteron electro-disintegration have yielded a substantial, but inconsistent body of data which could not be adequately described by theoretical models (see [1] for a review). To provide a richer input to theories, the deuteron program at Bates has been dedicated to separations of interference responses in a variety of kinematical settings. This could be achieved by simultaneous out-of-plane detection of ejected hadrons about the momentum transfer, thereby minimising systematic uncertainties and allowing for separation of both asymmetries and absolute responses [2, 3]. With this novel technique, competing effect in deuteron electro-disintegration (final-state interactions (FSI), meson-exchange currents (MEC), isobar configurations (IC), and relativistic corrections (RC)) can be probed precisely and selectively.

FIGURE 1. Preliminary results for the asymmetry A'_{LT} and the f_{TT} response as functions of p_m. Left panel: calculations of ref. [6] with ingredients marked in the figure. Right panel: calculations of ref. [6]: relativistic PWBA+FSI+RC (dashed), PWBA+FSI+MEC+IC (long-dashed), and full (solid), and of ref. [7]: PWBA+FSI (dashed-dotted). Note that both of these observables require out-of-plane detection.
Early deuteron electro-disintegration studies at MIT-Bates were focused on the quasi-elastic region \([4, 5]\). We report here on the measurements of \(d(e,e'p)\) in the dip region, where the asymmetries \(A_{LT}, A'_{LT},\) and \(A_{TT}\), as well as the responses \(f_{LT}, f'_{LT},\) and \(f_{TT}\) were measured at a beam energy of 800 MeV, a four-momentum transfer of \(Q^2 = 0.15 \text{GeV}^2\), and a missing momentum of 210 MeV/c. Preliminary results on the asymmetry \(A'_{LT}\) and the \(f_{TT}\) response are given in figure 1. The asymmetry \(A'_{LT}\) reflects the imaginary part of the LT interference term, and is thus highly sensitive to FSI. The \(f_{TT}\) response is very sensitive to an accurate inclusion of MEC and IC, and exhibits almost no dependence on relativity, contrary to \(A_{LT}\) and \(f_{LT}\). These results have been submitted for publication in Phys. Rev. Lett.

These measurements were performed with pulsed (\(\approx 1\%\)-duty-factor) beam, while the recent availability of the high-duty-factor extracted beam has challenged the OOPS Collaboration to continue the pursuit of the out-of-plane program, to extend it to higher missing momenta and into the \(\Delta\)-region. At higher energy transfers and higher missing momenta, an enhanced sensitivity to relativistic effects in \(A_{LT}\) and \(f_{LT}\), and to MEC and IC in \(A_{TT}\) and \(f_{TT}\) is expected. In the same kinematical region, the \(A'_{LT}\) and \(f'_{LT}\) will improve our understanding of \(\Delta - N\) interactions in the final state. In addition, these studies can be complemented with an enlarged set of polarisation observables, and can be performed with a significant decrease in experimental uncertainties.

**Upgrade and commissioning of the MIT-Bates South Hall and OOPS**

For the two most recent experimental efforts at MIT-Bates which required a high-duty-factor beam, major instrumental developments have taken place in the South Hall of the facility. A gantry support system allowing for out-of-plane positioning of two OOPS modules has been completed, and the fourth OOPS module has been commissioned. The OHIPS spectrometer has been upgraded for a momentum bite of 14\% and outfitted with a new vertical drift-chamber and additional scintillators and lead-glass detectors. Substantial modifications were made to the beam-line and readout electronics to conform to the CW beam extracted from the South-Hall storage ring [8].

**Studies of the N \(\rightarrow\) \(\Delta\) transition**

Studies of the \(\gamma^*N \rightarrow \Delta\) transition using OOPS have a long tradition [9]. They were originally aimed at precise extractions of the \(E2/M1\) and \(C2/M1\) multipole amplitude ratios which quantify the deviation of the nucleon or the \(\Delta\) from a spherical shape such as that assumed in the naive non-relativistic quark model or in models with a spherically-symmetric pion field. The initial effort to disentangle the quadrupole amplitudes from the dominating magnetic dipole component has now been augmented by more complete investigations. The \(LT, LT',\) and \(TT\) interference responses and the corresponding asymmetries have been isolated in wide kinematical regions. The \(p(e,e'p)\pi^0\) process has been studied in a range of invariant masses in the vicinity of the \(\Delta\)-resonance peak to explore the \(W\)-dependence of resonance and background contributions. A handle on the isospin
structure of the $N \rightarrow \Delta$ transition has been obtained by measurements of the concurrent $p(e,e'n)\pi^+$ process. Angular distributions in $\theta_{pq}^*$ (or $\theta_{pq}^\ast$) of protons (or $\pi^+$) have been measured to allow for a multipole decomposition of the responses.

**FIGURE 2.** The $R_{LT}$ response at $Q^2 = 0.126 \text{GeV}^2$ and $W = 1172, 1232$ and $1292 \text{MeV}$. The open square and the open circles denote the expected statistical uncertainties for the 2001 run. The shaded areas represent the systematic uncertainties. Full circles and squares: previously taken data [10, 11]. Model predictions are by Sato and Lee [12] and MAID [13]. The dashed curves correspond to calculations without the C2 contribution.

**FIGURE 3.** Expected statistical uncertainties for $R_{TT}$ and $R_{00}$ (see text) in the $\pi^0$-channel at $W = 1232 \text{MeV}$ and $Q^2 = 0.126 \text{GeV}^2$. The empty square in the right panel corresponds to about a third of the data taken in the run of 2001. (Data at $\theta_{pq}^* = 151^\circ$ was also taken.) For curves, see caption to figure 2.

During the 2001 run, the OOPS system was operated in the full, four-module setup for the first time, with a beam energy of $950 \text{MeV}$ at high duty-factor currents of up to $10 \mu\text{A}$. Two modules mounted on the gantry, in conjunction with the two in-plane modules, allowed for a decomposition of all unpolarised response functions, including $R_{TT}$. Running at forward angles and low proton momenta permitted a significant ex-
tension of the range of angular distributions. Figure 2 shows the $R_{LT}$ response which offers a most precise test of the existing phenomenological models. It is highly sensitive to the poorly-known resonance interference term $\text{Re}(S_{1+}^* M_{1+})$, except at the particular angle of $\theta_{pq} = 90^\circ$ where it is suppressed in favour of the maximal sensitivity to the background term $\text{Re}(S_{0+}^* M_{1+})$. The $R_{TT}$ response has never been measured before (see left panel of figure 3). This pure out-of-plane response is important in calibrating the absolute strength of the dominant $M_{1+}$ transition multipole. The particular combination of responses at $\theta_{pq}^* = 0^\circ$ (in parallel kinematics) and at an emission angle of $90^\circ$, $R_{00} \equiv (R_T + \epsilon LR_L)(90^\circ) + R_{TT}(90^\circ) - (R_T + \epsilon LR_L)(0^\circ)$ will also be extracted, since it exhibits a unique sensitivity to the E2 amplitude (see right panel of figure 3). Excellent beam conditions also enabled us to carry out a measurement of interference responses and cross-sections in the $p^+\text{-channel}$ at $W = 1232\text{ MeV}$, $Q^2 = 0.126\text{ GeV}^2$, and $\theta_{pq} = 44.5^\circ$, which is being analysed. The combined results of both reaction channels will yield information on the isospin structure of the $N \rightarrow \Delta$ transition.

**Virtual Compton scattering**

The Virtual Compton scattering experiment [14] was one of the highlights of this year’s extracted-beam program. The process $p(e,e'p)\gamma$ has been measured at five beam energies, corresponding to the outgoing-photon energies ranging from 28 to 115 MeV/c, at four-momentum transfer of $Q^2 = 0.05\text{ GeV}^2$. The physical goal was to measure the generalised polarisabilities of the proton at low momentum transfers and test several competing theories with great accuracy and minimal systematical uncertainties. The OOPS setup is excellently matched to access these observables at low momentum transfers, in particular due to a great out-of-plane suppression of the Bethe-Heitler background. Contrary to in-plane experiments which are primarily sensitive to the magnetic generalised polarisabilities, out-of-plane detection uniquely allows for a clear isolation of the electric part. A detailed analysis of the data is underway.

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