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A. TITLE:

Measurement of Recoil Polarization in the $^{16}O(\vec{e},e'\vec{p})$reaction with 4 GeV electrons

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C. THIS PROPOSAL IS BASED ON A PREVIOUSLY SUBMITTED LETTER OF INTENT

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Measurement of Recoil Polarization in the $^{16}O(\vec{e},e'\vec{p})$reaction with 2 GeV electron at CEBAF

D. ATTACH A SEPARATE PAGE LISTING ALL COLLABORATION MEMBERS AND THEIR INSTITUTIONS

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contact: Glashausser

Measurement of Recoil Polarization in the $^{16}O(\vec{e}, e'\vec{p})$ reaction with 4 GeV electrons

THE HALL A COLLABORATION

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Kent State University, University of Maryland, Massachusetts Institute of Technology
University of New Hampshire, National Institute of Science and Technology
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Abstract

The $^{16}O(\vec{e}, e'\vec{p})$ reaction will be investigated with 4 GeV polarized electrons in constant q kinematics. All three components of the recoil polarization of the proton will be measured for proton recoil momenta from 50 MeV/c to 300 MeV/c with a focal plane polarimeter in the hadron arm of Hall A spectrometer. The aim is a detailed understanding of the reaction mechanism effective in quasifree electron scattering. The total beam time estimated is 456 hours.

I. Introduction

Important problems highlighted in the new Long Range Plan for nuclear physics are the anomalies in the Coulomb sum rule for nuclei with masses greater than four and the related ratio of the longitudinal to transverse cross section in the quasielastic region which is significantly smaller than most theoretical estimates. Spectroscopic factors measured in exclusive electron scattering seem small. A long history of hadron work in this area yields spectroscopic factors which tend to be close to the shell model values for spherical nuclei, while the $(e, e'p)$ values are often 30% to 50% smaller. While there are many reasons to be suspicious of the hadron values, and, indeed, an important reason for studying this reaction has been to determine spectroscopic values with a reliable theory, it may be that the $(e, e'p)$ values are themselves not trustworthy.

A number of possible explanations of these problems have been proposed, ranging from more careful treatments of the reaction mechanism and better nuclear structure calculations to suggestions of quark effects and modifications of the nucleon properties inside the nuclear medium. In the absence of 100% duty factor machines with appropriate apparatus for the examination of all the properties open to the $(e, e'p)$ probe, it has not been possible to reliably distinguish between these theories. A conservative approach which we suggest here is to look at a number of new observables sensitive to various features of the reaction mechanism before making conclusions about exotic mechanisms. Many effects, such as relativistic dynamics, final state interactions, and off-shell effects are possibly important; it is important to isolate them and determine whether theory is adequate to account for them. It is important to measure the new observables which will give insight into specific aspects of this problem.

We propose to measure the recoil polarization of the outgoing protons in the $(\vec{e}, e'\vec{p})$ reaction on ^{16}O at 2 GeV with a polarimeter in the focal plane of the hadron spectrometer in Hall A. Such polarimeters have been in use for a number of years at proton facilities. At least five members of the collaboration are committed to building such a device for Hall A. The experiment we propose here should be considered as an initial step in what we expect to develop into a broad program of interesting polarization measurements in $(\vec{e}, e'\vec{p})$ at CEBAF. The ability to knock out a spinning proton from well inside the nucleus and observe its polarization outside with precision and accuracy is a most appealing feature of this new facility. To consider the possible impact of such recoil polarization measurements in $(\vec{e}, e'\vec{p})$, it is useful to look at developments in inelastic proton scattering when such experiments have come to dominate the field over the last few years. Measurements of sideways and longitudinal polarization were able to confirm the phenomenological success of scattering calculations based on the Dirac equation.[1] Combinations of polarization transfer parameters determined individual components of the effective NN interaction in the nuclear medium.[2] Sums and differences of sideways and longitudinal polarizations combined with the polarization normal to the scattering plane separate the spin longitudinal and spin-transverse contributions. The most interesting result[3] in that area is the apparent absence of the expected pionic enhancement around 1.75 fm^{-1}. Finally, measurements of the normal component alone permit a separation of spin- transfer S=1 and S=0 excitations and reveal unexpected S=1 strength at high excitation.[4]

Theoretical and experimental work on recoil polarization measurements in $(\vec{e}, e'\vec{p})$ are in their infancy, but the calculations which have been carried out suggest that such data are sensitive to many features of the reaction mechanism. Careful interpretation of such measurements should thus determine the reliability of the reaction model and point the way toward improvements. A formalism involving 18 possible structure functions has been developed.[5] For the experimentalist, particularly for an initial set of experiments, the physics is more direct in the values of the polarization observables themselves without specific recourse to the structure functions, and it is these that we will consider in theoretical calculations shown below. For example, for in-plane measurements, the normal component of the measured recoil polarization does not depend on the polarization of the beam and it is identically zero in the plane wave approximation. Thus it should be a sensitive indicator of final state interactions (FSI). Since the electron probe permits a proton to be knocked out from deep inside the nucleus, it is particularly important that these be well understood. Examination of various final states in the residual nucleus in exclusive measurements should allow FSI to be examined for varying penetration depths. The study of relativistic effects on particles ejected at different layers of the nuclear interior should also prove important. This has not been possible in proton scattering.

II. $^{16}O(\vec{e}, e'\vec{p})$

As an example of the sensitivity of the $(e, e'N)$ reaction to details of the reaction dynamics in many-body nuclei, the cross section and polarization are calculated for the knock out of a 500 MeV proton by a 2 GeV electron beam from the $1p_{1/2}$ shell of ^{16}O. One objective is to look for possible signatures of relativistic dynamics within the context of the distorted wave impulse approximation (DWIA).

First, it is necessary to define coordinate systems for locating the direction of the ejected proton and defining the direction of spin quantization. In Fig. 1, the incident electron with four-momentum $k=(\epsilon_k, \vec{k})$, scatters through an angle θ to a final four-momentum $q=(\omega, \vec{q})$. The electron scattering plane is defined by the three-momenta $\vec{k}$ and $\vec{k}'$ and also contains the three-momentum transfer q. The virtual photon is absorbed by the target nucleus, ejecting a proton with four-momentum $p' = (E(p'), \vec{p}')$, where $\vec{p}'$ is located relative to the coordinate system by the polar angle α and azimuthal angle β. The residual nuclear system recoils with four-momentum p_R=q-p$'$. The three-momenta $\vec{p}'$ and $\vec{p}_R$ define the hadronic plane, which is at an angle of β to the electron scattering plane and also contains the three-momentum transfer $\vec{q}$. Finally, it is necessary to define a coordinate system to be used in expressing the direction of spin quantization for the ejected proton. The unit vectors $\hat{n}$, $\hat{l}$, and $\hat{t}$, as shown in Fig. 1, form a righthanded coordinate system such that $\hat{l}$, is chosen to point in the direction of $\vec{p}'$, $\hat{n} = (\vec{q} \times \hat{l})/|\vec{q} \times \hat{l}|$, and $\hat{t} = (\hat{n} \times \hat{l})$.

The optical potentials used here are calculated[6] in the impulse approximation, which is a good approximation at the proton energy used here. Since the new dynamical content of Dirac models is the presence of virtual negative energy solutions to the Dirac equation in the nuclear wave functions, the Dirac optical potential is constructed such that when projected onto the positive energy plane wave Dirac space it yields the same results as the nonrelativistic optical potential. These optical potentials and the corresponding scattering states for them are produced by the optical model code WIZARD.[7] In a similar spirit "nonrelativistic" bound state wave functions are produced as a normalized positive energy projection of Dirac Hartree wave functions. Four calculations will be presented, the relativistic and nonrelativistic DWIA calculations, as described above, and plane wave impulse approximation calculations (PWIA) using either the relativistic or nonrelativistic bound state wave functions. Details of these calculations are presented in in refs. 8 and 9. It should be emphasized that although the two DWIA calculations do contain certain different dynamics, i.e. negative energy components, they are nevertheless very similar in that the physical input in the form of the nucleon-nucleon t matrices and the nuclear densities are identical. Therefore, the differences here are not as great as might be expected if a more complicated treatment of the nuclear many-body problem or quark dynamics were used to describe this reaction. Thus, the comparisons shown below represent, in some sense, a lower bound on the dynamical sensitivity of $(e, e'p)$.

Interesting effects are predicted if the ejected proton is detected in the electron scattering plane, but not constrained to be parallel to $\vec{q}$. The cross section for this case can be obtained from general formulas setting β=0 to give:

$$
\begin{aligned}
\left(\frac{d^3\sigma}{d\epsilon_{k'}d\Omega_{k'}d\Omega_{p'}}\right)_{h,s'} &= \frac{M|\vec{p}\,'|}{2\,(2\pi)^3}\left(\frac{d\sigma}{d\Omega_{k'}}\right)_{Mott} \\
&\times \; \left\{V_L\left(R_L + R_L^n S_n\right) + V_T\left(R_T + R_T^n S_n\right)\right. \\
&+ \; V_{TT}\left(R_{TT} + R_{TT}^n S_n\right) + V_{LT}\left(R_{LT} + R_{LT}^n S_n\right) \\
&+ \; \left. h\left[V_{LT'}\left(R_{LT'}^l S_l + R_{LT}^t S_t\right) + V_{TT'}\left(R_{TT'}^l S_l + R_{TT'}^t S_t\right)\right]\right\}
\end{aligned}
$$

where m is the proton mass and h is the helicity of the incident electron. The V's are kinematic factors and the R's are structure functions discussed in Ref. 5.

The projections of the proton spin vector are given by:

$$
S_n = \hat{n}\cdot\hat{s}'_R, \quad S_l = \hat{l}\cdot\hat{s}'_R, \quad S_t = \hat{t}\cdot\hat{s}'_R \;,
$$

when the direction of quantization of the ejected proton spin in its rest frame is given by $\hat{s}'_R$.

In the present calculation, then, according to Eq. 1, the unpolarized cross section contains contributions from R_L ,R_T ,R_{LT} and R_{TT}. The normal component of the polarization contains contributions from R_L^n ,R_T^n ,R_{LT}^n and R_{TT}^n; the longitudinal from R_{LT}^l and R_{TT}^l ; and the transverse from R_{LT}^t and R_{TT}^t. The normal polarization contributions are independent of electron polarization, while the other two components are electron polarization dependent.

There is considerable freedom to choose various paths across the $p_R - q$ plane. For this example, the path is given by $|\vec{q}| = |\vec{p}\,'|$ which is represented by the dashed line in Fig. 2. With this constraint and an electron beam energy of 2 GeV, each of the types of contributions to the cross section is dominated by a single response function to about the 80 percent level, the unpolarized by R_T, the normal polarization by R_{TT}^n, the longitudinal by R_{TT}^l, and the transverse by R_{LT}^t.

In Fig. 3, the cross section and the three components of the polarization vector are shown as a function of p_R for the ejection of a 500 MeV proton from the $1p_{1/2}$ shell of ^{16}O by an electron beam of 2 GeV under constant-q kinematics. The various line types correspond to the four calculations mentioned above. The semilog plots of the cross section show that the DWIA calculations exhibit a qualitative variation in shape from the PWIA at recoil momenta above the peak in the cross section. This is not the case for the same calculations in parallel kinematics. S_n, which vanished in PWIA, is on the order of 50% over most of the recoil momentum range and shows large differences between the two DWIA calculations for recoil momenta above p_R= 0.25 GeV.

Both S_l and S_t also show considerable sensitivity to the choice of calculation for the larger recoil momenta. Due to the large size of S_n and the great sensitivity to choice of calculations, it appears that the constant-q kinematics provides a promising means of discriminating among the various dynamical models of quasielastic electron scattering.

III. The Focal Plane Polarimeter

The focal plane polarimeter design is similar in principle to the polarimeters used successfully with protons at LAMPF, TRIUMF, IUCF, and SATURNE. Effectively measuring the left-right and up-down asymmetries in the scattering of the protons from a thick carbon analyzer yields the normal and sideways components of the polarization of the proton in the focal plane. These values are directly related to the polarization of the proton as it leaves the target.

At intermediate proton energy range, ^{12}C has been used as the analyzer due to its large analyzing power in the forward angle cone of the cross section. This facilitates the use of linear array of modest size wire chambers for the detection of the analyzed proton. In this energy range, the useful analyzing power for ^{12}C lies in the range of θ_c=5° to 20°.

Shown in Fig. 4 is the detector arrangement for the proposed polarimeter for the hadron HRS for Hall A. The polarimeter consists of a carbon analyzer up to 60 cm in thickness. A pair of front and a pair of rear wire chambers determine the incident and scattered angles, respectively. The segmented analyzer will allow variable thickness of carbon so that operation over a wide range of proton energies will be possible. In addition, Cherenkov counters are provided in the front end for pion rejection. Finally, a scintillation counter at the rear end provides the trigger for the polarimeter. The dimensions of the polarimeter detectors were determined so as to accept a 20° cone of protons scattered in the carbon. With this geometry, all values of ϕ_c for this cone are accepted by the polarimeter. The very forward angles are dominated by coulomb scattering and yield very little analyzing power.

Since the inclusive analyzing power and the cross section for $\vec{p}+{}^{12}C$ reaction are both slowly varying functions of the angles, the requirements on angular resolutions of each track is modest. The angular resolutions of the whole system is dominated by the multiple scattering in the thick analyzer. However, the centroid of the cone needs to determined very precisely in order to minimize instrumental asymmetry. Better that 1% systematic error in polarization can be achieved with angular resolution of about 0.1°.

The azimuthal asymmetry of the scattered protons is then used in determining the polarization of the incident proton. The azimuthal distribution of the $\vec{p}$ + analyzer scattering in the polarimeter is given by

$$I(\theta_c,\phi_c) = I_o(\theta_c)[1 + P_n A_c(\theta_c)\cos\phi_c + P_t A_c(\theta_c)\sin\phi_c]F(\theta_c,\phi_c) \tag{1}$$

where θ_c and ϕ_c are the polar and azimuthal scattering angle in the analyzer; $I_o(\theta_c)$ is the unpolarized cross section; $A_c(\theta_c)$ is the analyzing power of the analyzer; and $F(\theta_c,\phi_c)$ acceptance function of the FPP. Fourier transformation of the complete azimuthal distribution thus determines the the transverse components of the vector polarization.

The n and t components of the polarization in the focal plane are given by the asymmetries of the carbon scattering as:

$$P_n = \frac{2}{\pi\overline{A_c}}\left(\frac{R-L}{R+L}\right), \tag{2}$$

$$P_t = \frac{2}{\pi\overline{A_c}}\left(\frac{D-U}{D+U}\right), \tag{3}$$

where L, R, U, and D are the left, right, up and down yields in the polarimeter. If N_F is the number of the events that yield useful polarization information, and N_0 is the total events incident on the FPP, the efficiency of the FPP can be defined as:

$$\epsilon = {A_c}^2 f \tag{4}$$

where $f = N_F/N_0$ is then the fraction accepted by the FPP.

The statistical uncertainties in the measured polarizations are

$$\Delta P_n = \Delta P_t \approx \sqrt{\frac{2}{N_0\overline{A_c}^2 f}}. \tag{5}$$

IV. Spin Transport

In general, the polarization of the proton in the FPP $\vec{P}$ is related to the polarization of the proton as it leaves the target $\vec{S}$ by

$$\vec{P} = M_s M_p \vec{S} \tag{6}$$

where M_s the a unitary matrix representing the spin transport through the spectrometer. M_p represents the transformation matrix from the proton system to the spectrometer system.

Due to the precession of the proton polarization in the various bends inside the spectrometer, M_s may have off-diagonal elements; the leading contribution to this spin mixing in the spectrometer is usually from precession of protons in the dispersive plane of the dipole elements. However, focusing elements such as quadrupoles and fringe fields add differential corrections to the spin transport. In focusing spectrometers with many elements and large solid angle acceptance such as the HRS[2] at CEBAF, the form of M_s is non-trivial. These effects are currently being studied.

In the dispersive plane the only contribution of the spectrometer to the spin transport is due to the precession χ about $\hat{t}$ given by

$$\chi = \gamma(\frac{1}{2}.g_p - 1)\omega \tag{7}$$

where γ is the Lorentz factor, g_p is the proton g-factor, and ω is the net bend angle of the trajectory through the spectrometer. Then the measured polarizations are related to the reaction polarization as:

$$\begin{aligned} P_t &= hS_t && (8) \\ P_n &= \cos\chi S_n - h\sin\chi S_l && (9) \end{aligned}$$

These equations show that the determination of S_n and S_l can sometimes present problems. Near $\chi = \frac{\pi}{2}$, for example, the normal component of the scattered particle polarization becomes longitudinal at the focal plane and so it cannot be measured. Such energy holes occur around 0.1 and 1.15 GeV for the HRS. Around 500 MeV, both S_n and S_l contribute strongly to P_n and so they have to be separated with additional measurement. The most advantageous method depends on the experiment. For in-plane experiments the method is considerably simple. As seen from Eq.(1) S_n is independent of beam polarization h, where as both S_l and S_t flip signs with as the beam polarization is reversed. Thus electron polarization $\pm h$, the proton focal plane polarizations are:

$$\begin{aligned} P_t^+ &= hS_t^+ && (10) \\ P_t^- &= -hS_t^- && (11) \\ P_n^+ &= \cos\chi S_n - h\sin\chi S_l && (12) \\ P_n^- &= \cos\chi S_n + h\sin\chi S_l && (13) \end{aligned}$$

where the superscripts $\pm$ correspond to $\pm h$. From these equations one has:

$$S_t = \frac{P_t^+ - P_t^-}{2h} \tag{14}$$

$$S_n = \frac{P_n^+ + P_n^-}{2\cos\chi} \tag{15}$$

$$S_l = -\frac{P_n^+ - P_n^-}{2h\sin\chi} \tag{16}$$

Using Eqs.(15-17), and assuming $\Delta P_n^+ = \Delta P_n^-$ and $\Delta P_t^+ = \Delta P_t^-$ the the uncertainties are:

$$\Delta S_n = \frac{\Delta P_n^\pm}{\sqrt{2}\cos\chi} \tag{17}$$

$$\Delta S_l = \frac{\Delta P_n^\pm}{\sqrt{2}h\sin\chi} \tag{18}$$

$$\Delta S_t = \frac{\Delta P_t^\pm}{\sqrt{2}h} \tag{19}$$

In addition, with an unpolarized beam, $h = 0$, one has:

$$S_t = 0 \tag{20}$$

$$S_n = \frac{P_n}{\cos\chi} \tag{21}$$

Thus an unpolarized beam measurement will provide a very powerful method of checking instrumental asymmetries of the system as well as redundant measurement of S_n which will be an additional check on systematic errors.

V. Calibration

Extensive carbon analyzing power data exist for proton energies of up to 1.2 GeV in the angular range of 3° to 20° However, it is essential to calibrate the analyzing power of an FPP on-site; this will remove the false asymmetries of the FPP that are specific to the detector geometry, the FPP acceptance function, and the inclusiveness of the scattering in the analyzer. An on-site analyzing power measurement requires protons of known polarization. On-site calibration in $(\vec{e}, e'\vec{p})$ will be difficult. The best way seems to be the $\vec{e} + p \rightarrow e + \vec{p}$ reaction. The longitudinal polarization of the proton in this reaction is given by the magnetic form factor of the proton which is relatively well known. The longitudinal polarization is large for large electron scattering angles and may be used for analyzing power calibration.

VI. Count Rate Estimates

We have chosen do measurements for three values of recoil momenta 50 to 300 MeV/c in steps of 50 MeV/c. The kinematical variables are given in Table I.
The kinematics corresponds to $1p_{1/2}$ proton knockout from ^{16}O with the following fixed parameters:

Incident Beam Energy:	4.000	GeV
Scattered electron energy:	3.488	GeV
Electron scattering angle:	14.80	deg
Scattered proton Energy:	0.5	GeV
Scattered proton momentum:	1.09	GeV/c
Momentum transfer:	1.09	GeV/c

Cross sections have been estimated with van Orden's response functions. Count rates were calculated from the cross sections with the following target and spectrometer parameters:

^{16}O cryo gas target:	50	mg/cc
Target length:	10	cm
Luminosity:	2.5×10^{35}	$cm^{-2}sec^{-1}$
Beam current:	200	μA
Electron beam polarization:	40	%
Electron Arm solid angle:	7.8	msr
Proton arm solid angle:	7.8	msr
Momentum acceptance:	10	%

Table I. Kinematics and Rates				
p_R (GeV/c)	θ_p (deg)	θ_{pq} (deg)	σ^0 (nb/sr^2/MeV)	Coinc. Rate (hour^{-1})
0.05	57.46	2.63	3.6500	260755
0.10	60.10	5.26	5.3520	382230
0.15	62.73	7.89	2.4671	176260
0.20	65.37	10.54	0.4293	30670
0.25	68.02	13.19	0.0588	4200
0.30	70.69	15.85	0.0173	1236

For 500 MeV protons the FPP parameters are:

Average analyzing power ($\overline{A_c}$):	0.25
Fraction accepted in the FPP (f):	0.20
Precession angle (χ):	124°

We propose to measure polarizations to a statistical uncertainty $\Delta S_n = \Delta S_l = \Delta S_t = \pm 0.05$. Using Eq(18-20), this translates to uncertainties in P's and required number of coincidence events N_0:

$\hat{n}$-type measurements: $\Delta P_n = 0.039$, $N_0 = 1.0\times^5$
$\hat{l}$-type measurements: $\Delta P_n = 0.023$, $N_0 = 3.0\times^5$
$\hat{t}$-type measurements: $\Delta P_t = 0.070$, $N_0 = 3.0\times^4$

Since all three components are measured simultaneously with polarized beam, it is the determination of S_l, that determines the running time. In addition, we will require some unpolarized beam time at the lowest recoil momentum for systematic checks; and polarized beam time for calibration checks of the polarimeter. The required running times are summarized in Table II. Note that we have added 50 hours of unpolarized beam time for systematics checks and redundant measurement of P_n at 100 MeV/c. Furthermore, out of the 28 hours of polrized beam time at 100 MeV/c, 24 hours will be devoted to FPP analyzing power calibration checks.

Table II.Run Time Estimates					
p_R (MeV/c)	Beam Polarization	ΔP_n	ΔP_l	ΔP_t	Time (hours)
	Calibration				
100	0.0	0.006	-	-	50
100	0.4	0.008	-	-	24
	Data				
50	0.4	0.020	0.012	0.036	4
100	0.4	0.017	0.010	0.030	4
150	0.4	0.019	0.011	0.033	8
200	0.4	0.030	0.018	0.055	16
250	0.4	0.032	0.019	0.058	100
300	0.4	0.039	0.023	0.070	250
				Total	456

Summary

In summary, we propose to measure recoil polarization of protons knocked out from the $1p_{1/2}$ state of ^{16}O with 4 GeV polarized electrons with the HRS pair in Hall A at CEBAF. All three components of the recoil polarization of the proton will be measured for proton recoil momenta from 50 MeV/c to 300 MeV/c with a focal plane polarimeter in the hadron arm. The aim is a detailed understanding of the reaction mechanism effective in quasifree electron scattering. The total beam time estimated is 456 hours.

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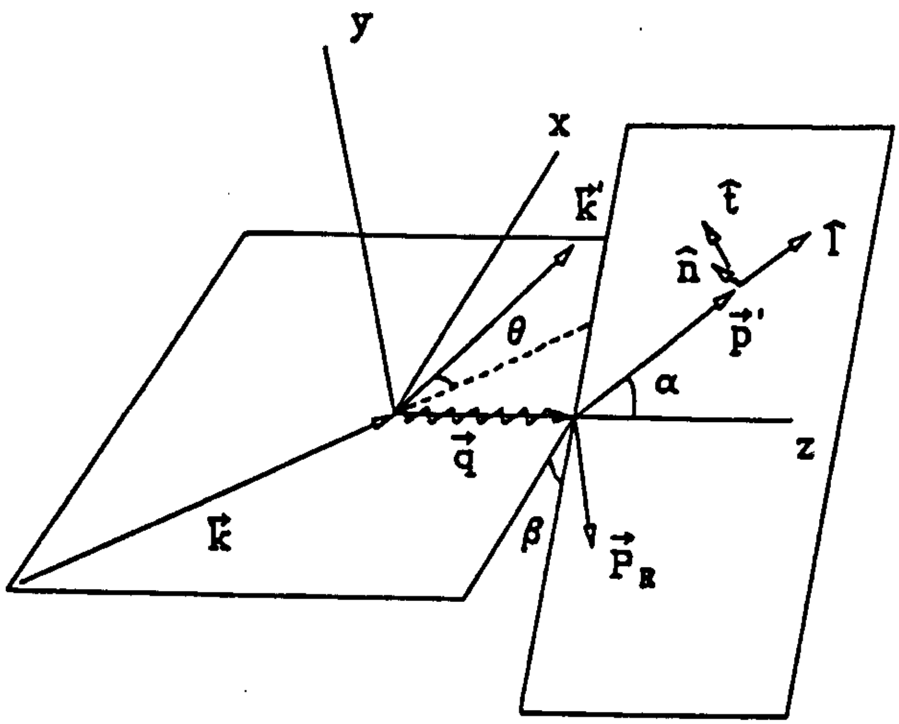


Fig. 1 Coordinate system chosen for the representation of the $(\vec{e}, e'\vec{N})$ reaction.

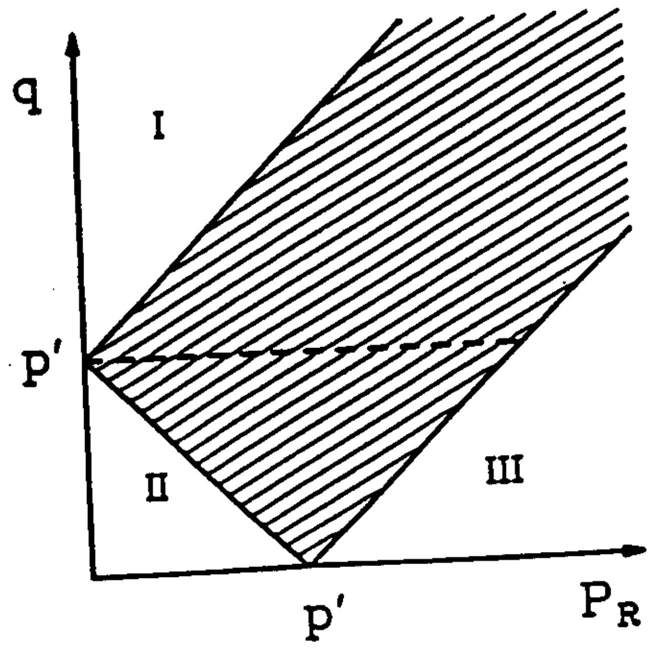


Fig. 2 The kinematically allowed (hatched) region for the $(\vec{e}, e'\vec{N})$ reaction.

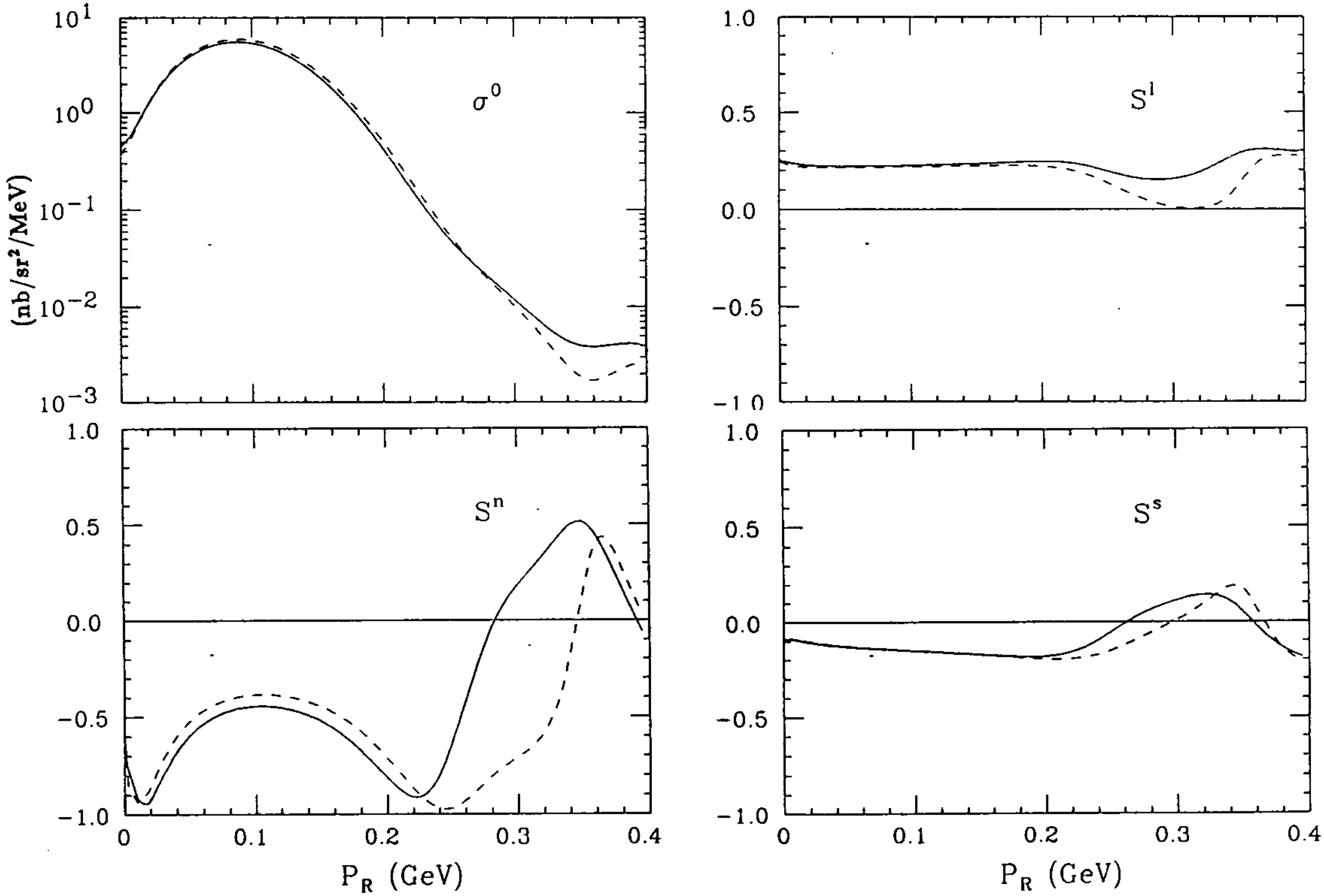
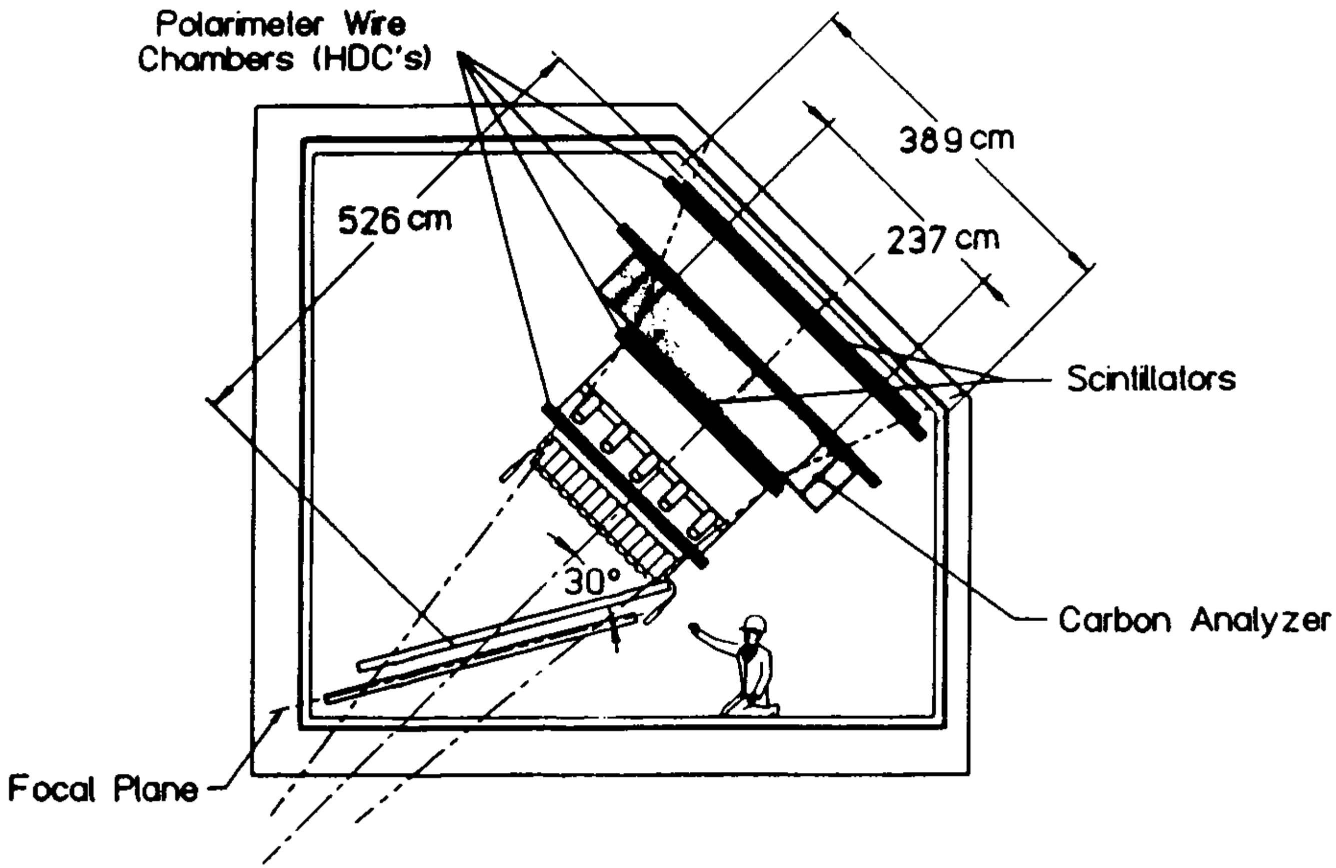


Figure 3. Cross section and polarization vector for the ejection of 500 MeV proton from the $1p_{1/2}$ shell of ^{16}O in constant-q kinematics. The incident electron energy is 4 GeV. Calculations are shown for Dirac DWIA (solid line) and for nonrelativistic DWIA (dashed line).



Hall A Hadron Arm Focal Plane Polarimeter

Fig. 4