Measurement of the Induced Proton Polarization $P_n$ in the $^{12}$C(e,e'p) Reaction

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(March 30, 2022)

The first measurements of the induced proton polarization, $P_n$, for the $^{12}$C(e,e'p) reaction are reported. The experiment was performed at quasi-free kinematics for energy and momentum transfer $(\omega, q) \approx (294 \text{ MeV}, 756 \text{ MeV/c})$ and sampled a recoil momentum range of 0-250 MeV/c. The induced polarization arises from final-state interactions and for these kinematics is dominated by the real part of the spin-orbit optical potential. The distorted-wave impulse approximation provides good agreement with data for the $1s_{1/2}$ part of the spin-orbit optical potential. The data for the continuum suggest that both the $1s_{1/2}$ shell and underlying $\ell > 1$ configurations contribute.

Single-nucleon knockout by electron scattering is sensitive to both the nuclear spectral function and to the properties of the electromagnetic current in the nuclear medium; recent reviews of this subject may be found in Refs. [1–5]. Single-hole momentum distributions for discrete states of the residual nucleus are usually extracted from spin-averaged differential cross section data. Additional insight into the reaction mechanism can be obtained by separation of the unpolarized response functions. Even more discriminating tests of the reaction mechanism are provided by measurements of the polarization of the ejectile. In this Letter we report the first measurements of recoil polarization for protons ejected from a nucleus of $A > 2$ via electron scattering, specifically the $^{12}$C(e,e'p) reaction.

Nucleon knockout reactions of the type $A(e,e'N)B$ initiated by a longitudinally polarized electron beam and for which the ejectile polarization is detected may be described by a differential cross section of the form

$$\frac{d\sigma_{hs}}{d\varepsilon_f d\Omega_e d\Omega_N} = \sigma_0 \frac{1}{2} [1 + P \cdot \sigma + h(A + P' \cdot \sigma)], \quad (1)$$

where $\varepsilon_f$ is the scattered electron energy, $\sigma_0$ is the unpolarized cross section, $h$ is the electron helicity, $s$ denotes...
the nucleon spin projection upon $\sigma$, $P$ is the induced polarization, $A$ is the electron analyzing power, and $P'$ is the polarization transfer. Thus, the net polarization of the ejectile nucleon $\Pi$ has two contributions of the form

$$\Pi = P + hP',$$

where $|h| \leq 1$ is the longitudinal beam polarization. Each of the observables may be expressed in terms of defined by the basis vectors with respect to a helicity basis in the barycentric frame the polarization transfer lies within the scattering plane. Thus, the net polarization of the ejectile must be normal to the scattering plane while the polarization transfer lies within the scattering plane. Hence, the net ejectile polarization for an unpolarized beam and coplanar kinematics is normal to the scattering plane. The recoil polarization is usually calculated with respect to a helicity basis in the barycentric frame defined by the basis vectors

$$\hat{t} = \frac{p'}{|p'|}, \quad \hat{n} = \frac{q' t}{|q' t|}, \quad \hat{P}' = \hat{n} \times \hat{t}.$$

For this experiment performed with $p'$ (the ejectile threemomentum) on the large-angle side of $q$ (the three-momentum transfer), characterized by $\phi_{pq} = 180^\circ$, the $\hat{n}$ direction is vertically downwards in the laboratory.

It can be shown that $P_n$ for the one-photon exchange approximation vanishes in the absence of final-state interactions (FSI) between the ejectile and the residual system. Within the distorted-wave impulse approximation (DWIA) these final-state interactions are usually described by an optical-model potential of the form

$$U(r) = U^C(r) + U^{LS}(r)\sigma \cdot L$$

where $U^C$ and $U^{LS}$ are complex central and spin-orbit potentials, respectively. Although the optical potential for elastic scattering from the ground state can be fit to nucleon-nucleus scattering data, no such data exists for the excited states of the residual system that are reached by knockout. Furthermore, electromagnetic knockout reactions probe the spatial distributions of these potentials differently than do elastic scattering experiments. The dynamics of FSI in the continuum may also be more complicated, requiring explicit channel coupling. Therefore, $P_n$ provides an important independent test of the optical model, especially for final states in the continuum.

The proton polarization was measured in the newly commissioned Focal Plane Polarimeter (FPP) of a carbon analyzer bracketed by two pairs of multi-wire proportional chambers. A fast hardware trigger system was used to reject small-angle Coulomb scattering events which have small analyzing power. The analyzing power for $120 \leq T_p \leq 200$ MeV was measured at the Indiana University Cyclotron Facility using proton beams of known polarization with this FPP. These data were combined with the world’s $p - ^{12}$C analyzing power data for $155 \leq T_p \leq 300$ MeV and parameterized in the form introduced by Aprile-Giboni et al. For this experiment, a 9-cm thick carbon analyzer was used which provided an average analyzing power of 0.53. The uncertainty in the measured proton polarization due to the analyzing power was 1.6%. Details concerning the spectrometers and the FPP can be found elsewhere.

The electron spectrometer was set at a scattering angle of $120.3^\circ$ and a central momentum of 280 MeV/c. The proton spectrometer was set at a central momentum of 756 MeV/c: three angle settings ($22.0^\circ, 26.6^\circ$, and $31.0^\circ$) were used to cover the missing momentum range $0 \leq p_m \leq 250$ MeV/c. The ejectile kinetic energy for the ground state of $^{11}$B was approximately constant at a central value of 274 MeV and $Q^2 = q^2 - \omega^2 = 0.5$ (GeV/c)$^2$. The data from the three angle settings were combined and binned into recoil momentum bins of 50 MeV/c ranging from 0 to 250 MeV/c. They were further separated into four missing energy (E$_m$) bins: A bin from 16.0 to 20.4 MeV where the data were dominated by $1p_{3/2}$ shell knockout, two bins from 28.0 MeV to 39.0 MeV and from 39.0 MeV to 50.0 MeV where the reaction is a mixture of $1s_{1/2}$ shell knockout and continuum effects, and a bin from 50.0 MeV to 75.0 MeV where the reaction is primarily due to the continuum. The measured polarizations were corrected for accidental coincidences. The signal to noise ratio ranged from 17:1 for $1p_{3/2}$ shell knockout in the 100-150 MeV/c recoil momentum bin to $\approx$ 1:1 for the 50 $\leq E_m \leq 75$ MeV bins.

The polarization at the target is related to the polarization at the focal plane by $P_n^{gt} = S_{nx} \cdot P_n^{fp}$ where $S_{nx}$ is a spin-transport coefficient that includes transformations between coordinate systems, precession in the magnetic fields, and the effects of finite acceptance. For our application, $S_{nx} \approx (\cos \chi_0)^{-1}$, where $\chi_0 = 207.3^\circ$ is the mean spin-precession angle. Small corrections for finite acceptance were made by modifying the Monte Carlo program MCEEP to use the spin-transport matrices produced by COSY. The net effect upon $S_{nx}$ varies slowly with $(p_m, E_m)$ and was found to be in the range $\pm$.
0.03 ± 0.03, where the uncertainty includes an estimate of the model dependence of the Monte Carlo simulation. The extracted transverse polarization \( P_t \) averaged over all bins, was \( P_t = 0.008 ± 0.018 \). Also, bin by bin, \( P_t \) was consistent with zero, as expected for an unpolarized beam. Instrumental false asymmetries for the \( P_n \) measurements were shown to be less than \( ± 0.005 \) from the elastic hydrogen FPP measurement \( [13] \). Because the polarization of elastically scattered protons from an unpolarized electron beam is constrained to be zero in the one-photon exchange limit, any measured polarization provides a means of normalizing the FPP.

Measured polarizations for several bins of missing energy are compared in Fig. 3 with DWIA calculations using the effective momentum approximation: details of the DWIA formalism may be found in Refs. \([14,16]\). We used momentum distributions fitted to \( ^{12}\text{C}(e, e'p) \) data by van der Steenhoven et al. \([17,18]\) and the energy-dependent \( ^{12}\text{C} \) optical potential of Cooper et al. \([19]\) with their best fit for carbon (EDAIC). The Dirac scalar and vector potentials were transformed to equivalent Schrödinger form and the Darwin nonlocality factor was included. Fig. 3 shows that DWIA calculations agree reasonably well with the \( P_n \) data for the \( 1p_{3/2} \) shell with a systematic underestimate of about ten percent. The comparison between DWIA calculations and data for the \( 1s_{1/2} \) is complicated by the presence of an underlying continuum that may contain significant \( \ell > 0 \) contributions. The induced polarization for \( 28 \leq E_m \leq 39 \) MeV is consistent with DWIA calculations for the \( 1s_{1/2} \) shell, whereas for \( E_m > 50 \) MeV (Fig. 2) we find a positive \( P_n \). This result suggests that the polarization of the continuum beneath the \( 1s_{1/2} \) shell, composed primarily of configurations with \( \ell > 1 \), is positive and tends to dilute the negative polarization expected for the \( 1s_{1/2} \) shell. Thus, the intermediate bin, \( 39 \leq E_m \leq 50 \) MeV, retains little net polarization where these opposing contributions tend to cancel. Note that this effect increases with increasing missing momentum.

The sensitivity to the choice of optical potential is illustrated in Fig. 3 by comparing calculations based upon the EDAIC and EEI optical models. The EEI model folds a density-dependent empirical effective interaction (EEI) with the nuclear density. The empirical effective interaction is fitted to proton-nucleus elastic and inelastic scattering data for several states of several targets simultaneously using procedures developed in Ref. \([20]\). However, because the nearest available energies for the EEI are 200 and 318 MeV \([21]\), a linear interpolation with respect to ejectile energy was performed. We find that the EEI model yields somewhat stronger \( P_n \) and better agreement with the data for the \( 1p_{3/2} \) shell.

It is also instructive to examine the contributions of various components of the optical potential separately. These are illustrated in Fig. 1 by calculations using the EDAIC potential in which all other parts of the optical potential were turned off. Of course, these separated polarizations do not simply add when the full potential is used. There are two dominant sources of induced polarization: the imaginary central \( (W^C) \) and real spin-orbit \( (V^{LS}) \) potentials.

The most familiar source of induced polarization is produced by \( W^C \) and arises from the correlation between absorption and initial spin that is commonly known as the Newns polarization \([22,23]\) or the Maris effect \([24]\). However, spin-orbit distortion is the largest source of induced polarization for the present reaction. Although the effect of spin-orbit distortion upon ejectile polarization has been studied for \((d, p)\) reactions at low energies \([23,24]\), there exists little data for the induced polarization in nucleon knockout at intermediate energies. The nature of the spin-orbit effect can be understood using a semi-classical argument \([25]\) based upon the spin-orbit force

\[
F_{LS}^{(r)} = -\nabla (V_{LS}^{r}(\sigma \cdot L)) = -\dot{\sigma} \frac{\partial V_{LS}^{r}(\sigma \cdot L)}{\partial \vec{r}} - \sigma \cdot L + V_{LS}^{(r)}\sigma \otimes \vec{p}'.
\]

The first term is a central spin-orbit force which produces spin-correlated changes in the magnitude of the ejectile momentum and is most important for parallel kinematics; however, its effect is generally quite small because it averages over a bipolar function. The second term is most effective in quasiperpendicular kinematics where spin-up (spin-down) protons are deflected toward the right (left), which for \( \phi_{pq} = 180^\circ \) increases (decreases) the missing momentum. The polarization induced by this effect is greatest where the slope of the initial momentum distribution is largest. When \( \ell > 0 \) a shift of the rising slope of the momentum distribution toward larger angles for spin-up yields \( P_n > 0 \), whereas the falling slope of an \( \ell = 0 \) momentum distribution yields \( P_n < 0 \) for small \( p_m \). Therefore, this argument explains the sign of \( P_n \) for both the \( 1p_{3/2} \) and \( 1s_{1/2} \) states at small \( p_m \). Furthermore, this argument suggests that zero crossings in the \( V_{LS} \) contribution to \( P_n \) should occur near extrema of the momentum distribution, but their precise locations depend upon more complicated geometrical and refractive effects.

In Fig. 2 we compare the induced polarization for the deep continuum, \( 50 \leq E_m \leq 75 \) MeV with DWIA calculations for single-nucleon knockout from several orbitals that might be populated by \( 2p2h \) ground-state correlations. Although the overlap functions are not necessarily those of the mean field, we used Woods-Saxon potentials with depths chosen to reproduce central missing energy \( E_m = 62 \) MeV. For \( p_m > 100 \) MeV/c we find that knockout from the \( 1d_{5/2} \) or \( 1f_{7/2} \) orbital would produce a positive polarization. In addition, the extra node in the \( 2s_{1/2} \) wave function leads to a rapid sign change in its contribution to the induced polarization in
the vicinity of \( p_m \sim 180 \text{ MeV}/c \). Although this feature will probably be smeared in a more realistic continuum calculation, a small admixture of this configuration could have an important effect upon the induced polarization for the continuum at large \( p_m \) where the \( 1s_{1/2} \) contribution is decreasing rapidly. Therefore, although more detailed calculations are needed to properly evaluate the effect of multinucleon mechanisms both in final-state interactions and in the absorption of the virtual photon, it appears that single-nucleon knockout from orbitals above the Fermi level that would be unpopulated in the absence of two body correlations could account for the positive polarization we observe in the deep continuum.

Summarizing, we have performed the first measurements of induced polarization for the \( ^{12}\text{C}(e, e'p) \) reaction in quasiperpendicular kinematics for \( p_m \leq 250 \text{ MeV}/c \). The induced polarization is primarily sensitive to final-state interactions and we have illustrated the roles of each component of the optical potential. For the present kinematics, the real part of the spin-orbit potential is the dominant source of \( P_n \). The data for \( 1p_{3/2} \) shell are in reasonable agreement with standard DWIA calculations based upon phenomenological optical potentials fit to elastic scattering data for the ground state. Slightly better agreement with the \( 1p_{3/2} \) shell data is obtained using a density-dependent empirical effective interaction fitted to proton-nucleus elastic and inelastic scattering data. The data for the \( 1s_{1/2} \) region are also consistent with DWIA calculations provided that allowance is made for the opposite polarization arising from more complicated contributions to the continuum. Improved statistical precision should allow the multipole structure of the continuum and variations of the final-state interactions for highly excited residual systems to be probed. Future experiments with polarized electron beams will measure the induced polarization transfer observables that are expected to be sensitive to two-body currents and/or modification of the one-body electromagnetic current, but relatively insensitive to final-state interactions. Such data, combined with precise \( P_n \) measurements, will result in considerably more stringent tests of the dynamical ingredients of the \( (e,e'N) \) process.

**ACKNOWLEDGMENTS**

The authors gratefully acknowledge the work of the staff at MIT-Bates. We also thank N.S. Chant for discussions of the history of induced polarization in knockout and transfer reactions. This work was supported in part by the U.S. Department of Energy under Grant No. DE-FG05-89ER40525 and DE-FG05-90ER40570 and by the National Science Foundation under Grants Nos. PHY-89-193959, PHY-91-12816, PHY-93-11119, PHY-94-05315, PHY-94-09265, and PHY-94-11620.

![FIG. 1. Polarization for the \( ^{12}\text{C}(e, e'p) \) reaction. Data for \( E_m \leq 24 \text{ MeV} \) are compared with DWIA calculations for 1p_{3/2} knockout (top). Data for 28 \leq E_m \leq 39 \text{ MeV} \) and 39 \leq E_m \leq 50 \text{ MeV} \) (bottom) are compared with calculations for 1s_{1/2} knockout, although the relative importance of underlying \( \ell > 0 \) configurations increases with \( p_m \) and \( E_m \). Note that a symmetric \( \pm 2 \text{ MeV}/c \) shift in recoil momentum has been put in to separate the data from the two bins. The solid curves show DWIA calculations using an optical potential based upon a density-dependent empirical effective interaction (EEI). The long dashed curves use the EDAIC potential, whereas other curves show the effect of individual components of the optical potential using the EDAIC potential.](image1)

![FIG. 2. Polarization for the \( ^{12}\text{C}(e, e'p) \) reaction. Data for 50 \leq E_m \leq 75 \text{ MeV} \) are compared with calculations using the EDAIC potential for single-nucleon knockout from various orbitals.](image2)
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