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Determination of analyzing powers for 189 MeV proton elastic scattering on ^{12}C

S. W. Wissink, S. P. Wells, E. J. Stephenson, J. Sowinski, A. D. Bacher, P. Li,
J. Lisantti,* C. Olmer, A. K. Opper,† R. Sawafta,‡ and P. Schwandt
Indiana University Cyclotron Facility, Bloomington, Indiana 47408

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The analyzing power A_y for proton elastic scattering on ^{12}C has been precisely and absolutely determined at three scattering angles ($\theta_{\text{lab}}=16.3°$, 17.3°, and 18.3°) at an incident proton energy of 188.9 MeV. The technique employed requires statistically high quality polarization transfer measurements, combined with the constraints imposed on polarization observables for reactions with the spin structure $\frac{1}{2}+0 \rightarrow \frac{1}{2}+0$. These results represent some of the most accurately known spin observables at intermediate energies and serve as calibration points for secondary standards.

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Reaction analyzing powers (and recently other spin observables as well) are frequently measured with statistical errors that are significantly smaller than the corresponding systematic uncertainties. These latter effects are often due primarily to lack of precise knowledge of the incident beam polarization, either in absolute terms or even in a relative sense, i.e., from one measurement to the next. Though recent progress in the development of in-beam high-energy polarimetry [1] has made it possible to monitor these relative fluctuations quite reliably, an absolute determination of A_y requires that the polarimeters used be calibrated against a well-determined analyzing power standard, few of which exist in the intermediate-energy regime. Conventional double-scattering experiments [2-4] provide such information in principle, though in practice the method is subject to many sources of uncertainty, both statistical and systematic.

We have employed another technique [5], previously unused at intermediate energies, which relies on the quadratic relationship that exists among three of the polarization observables in $\frac{1}{2}+0 \rightarrow \frac{1}{2}+0$ spin configuration reactions [6], namely,

$$A_y^2+D_{LL'}^2+D_{LS'}^2=1\,. \tag{1}$$

[In this case, because there can be only three independent observables, it is also true that

$$\begin{gathered} P=\pm A_y,\ D_{NN'}=\pm 1\,, \\ D_{SS'}=\pm D_{LL'},\ D_{SL'}=\mp D_{LS'}\,, \end{gathered} \tag{2}$$

where the upper (lower) sign is applicable for transitions between states of the same (opposite) parity.] A direct consequence of the quadratic nature of Eq. (1) is that by working in kinematic regimes where A_y is known to *approach* ±1, one can then *determine* A_y very accurately through much less precise measurements of the in-plane polarization transfer coefficients $D_{LL'}$ and $D_{LS'}$, which necessarily become small. In this context, it is useful to rewrite Eq. (1) in the form

$$|A_y|=(1-D_{LL'}^2-D_{LS'}^2)^{1/2}\,. \tag{3}$$

As an example, if both $D_{LL'}$ and $D_{LS'}$ are independently measured to be 0.05 ± 0.02, then one would find $|A_y|=0.995\pm0.0014$, an order-of-magnitude reduction in the statistical error.

Moreover, because one is using a *null* method, and therefore searching for small, rather than large, asymmetries, experimental sensitivity to many potential sources of systematic error are also minimized as $|A_y|$ approaches 1. Accurate knowledge of the beam polarization is not needed to determine a zero crossing; uncertainties in the effective analyzing power of the polarimeter used to measure the scattered proton polarization become less important for the same reasons. Possible errors due to spin dependence in the dead-time corrections and detector responses also become negligible with this technique because the counting rates are essentially equal for all horizontal (in the scattering plane) incident spin orientations. [These types of error represent a significant concern for more conventional double-scattering measurements carried out at large values of A_y, in which vertically (perpendicular to the scattering plane) polarized beams are used.] It is also important to note that a spin flip at the polarized ion source results in an exact spin reversal of the in-plane polarization components *even for the scattered beam,* a symmetry which does *not* apply to the polarization component perpendicular to the scattering plane. The polarimeter for the scattered particles therefore functions as a true double-arm polarimeter, and standard analysis techniques can be employed to eliminate sensitivity to all instrumental asymmetries to at least first order.

To make these measurements most useful as calibration standards, we have chosen targets that are easy to obtain and handle, and reactions with large cross sections in angle ranges where A_y is known to be close to ±1. Pro-

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*Present address: Department of Physics and Engineering, Centenary College of Louisiana, Shreveport, LA 71134.

†Present address: Department of Physics, University of Alberta, Edmonton, Canada AB T6G 2J1.

‡Present address: Physics Department, Brookhaven National Laboratory, Upton, NY 11973.

ton elastic scattering near 190 MeV on ^{12}C satisfies all these requirements. The use of lighter nuclei also results in relatively slowly varying angular distributions that do not impose severe restrictions on the angular resolution of the detector system, and allows for clean separation of the elastic peak of interest from those due to contaminant nuclei in the target material. The resolution constraints are therefore very modest and no background subtraction is required, thus removing most ambiguities in the extraction of peak yields.

In this paper we first describe briefly the experimental procedures employed, then present and discuss our main results, and address several issues related to systematic error concerns. A more detailed description of the equipment, data acquisition and reduction techniques, and methods of error analysis, plus the results of similar measurements performed at other energies, will be provided in a forthcoming paper.

The experiment was carried out at the Indiana University Cyclotron Facility with a 188.9 ± 0.3 MeV polarized proton beam. The beam energy was determined by closing down slits tightly around the beam just before and after a calibrated 45° analysis magnet. The energy spread of the beam was estimated to be less than 150 keV. The proton beam was produced using a standard atomic beam polarized ion source [7]. A low-energy polarimeter [8], mounted between the injector and main stage cyclotrons, was used approximately once each day to monitor the normal component of the beam polarization (0.78–0.80) and to check for differences in the polarization magnitudes between the "up" and "down" spin states (always <0.01).

At various points throughout the experiment, vertically polarized protons were required, and the beam could be transported directly to the experimental area. To measure the "in-plane" spin transfer observables $D_{LL'}$ and $D_{LS'}$, however, the polarization vector of the proton beam must be rotated into the (horizontal) reaction plane at the desired orientation (ϕ) with respect to the beam direction. This was accomplished through the use of two superconducting solenoids, with magnetic fields parallel to the proton momentum, positioned upstream and downstream of the 45° analysis magnet. At this beam energy, the precession of the proton's spin (about the vertical axis) induced by the intervening dipole (96.9°) is sufficiently close to 90° that one can orient the final proton polarization vector to point in almost any direction desired through appropriate adjustment of the two solenoid currents. High-energy in-beam (transmission) $p+d$ polarimeters [1] continuously monitored both the normal (vertical) and sideways polarization components of the beam. By locating a polarimeter immediately downstream of each solenoid, and knowing the spin precession angle in each, complete information on the proton polarization state can be obtained, without any prior assumptions as to the polarization of the beam extracted from the cyclotrons [9].

The elastically scattered protons were detected and momentum analyzed with the K600 magnetic spectrometer system [10] (a quadrupole-dipole-dipole configuration with a horizontal bend plane), and their polarization measured in a polarimeter [focal plane polarimeter (FPP)] [9,11] located just beyond the focal plane detectors. The unscattered beam was collected in a Faraday cup positioned within a shielded dump. Typical beam currents for production running were between 5 and 10 nA. The targets consisted of isotopically enriched ($\sim$99.9%) ^{12}C, and were approximately 11 mg/cm^2 thick. During acquisition of the spin transfer data, the acceptance of the spectrometer was defined by a rounded slot 1.27 cm wide and 2.54 cm high milled through a piece of thick ($\sim$1.2 cm) brass positioned perpendicular to the scattered flux and placed 71.3 cm from the center of the scattering chamber. This corresponds to a subtended half-angle $\Delta\theta$ of 0.51° and a solid angle of 0.568 msr.

By matching the momentum dispersion of the incident beam to that of the spectrometer, an energy resolution of $\sim$55 keV (full width at half maximum) was maintained on the focal plane throughout the run. This was more than sufficient to separate the ^{12}C elastic events from those due to other reactions. At the angles studied, the closest contaminant peak, from elastic scattering on ^{13}C, was typically 120 keV away and weaker by roughly 3 orders of magnitude. It is also known [12] that at 200 MeV the analyzing powers of ^{12}C and ^{13}C differ by less than 0.05 at these values of momentum transfer.

The efficiencies of the four FPP multiwire proportional chambers were in excess of 99% at all times. The two vertical drift chambers (VDC's) used in the focal plane require a significantly more complex algorithm for event reconstruction, and yielded a total efficiency in the range of 82–85%. The VDC efficiencies only rarely differed by more than 1% for the two proton spin states. The combined computer and electronic dead time was kept below 10% for all runs (8% was typical), and showed no systematic spin dependence for the in-plane polarization data.

These data are the first in-plane polarization transfer observables measured with the K600 spectrometer system, and extensive calibration tests were integrated into the data collection program. This ensured, for example, that the effective analyzing power assumed for the focal plane polarimeter was determined using the same beam energy, spectrometer angle calibration, and analysis software used for the actual measurements. Details on the techniques and results of the calibration procedures will appear in a later article, and will be presented only schematically below.

The absolute scattering angle for the spectrometer was determined by observing a kinematic crossing between protons elastically scattered from ^{12}C and protons inelastically scattered from the first 2^+ state in ^{58}Ni at 1.45 MeV. At $T_p = 200$ MeV, this crossing occurs in the laboratory frame at $\theta_0 = 18.10°$, and changes with beam energy as $\partial\theta_0/\partial T_p = -0.050°$/MeV. These data, taken simultaneously using a composite target, determined the scattering angle to $\pm 0.1°$. The spectrometer was then rotated 36.2° (as measured by a digital encoder) to $\theta_{\text{lab}} = -18.1°$ (beam right) and the crossing confirmed to within the same accuracy. This procedure therefore not only determined the offset in the angle calibration, but also checked the gain of our digital encoder.

To perform in-plane spin transfer measurements, one must know the horizontal polarization magnitude (P_0) and orientation (ϕ) of the incident beam, the spin precession angle (α) of the scattered proton polarization about the vertical axis within the spectrometer magnets, and the effective analyzing power of the polarimeter ($\mathcal{A}_{\rm FPP}$) for sideways polarizations. The beam polarization parameters can be determined from the high-energy polarimeters, while α is obtained from the angular information provided by the focal plane VDC's. To determine $\mathcal{A}_{\rm FPP}$, we note [13] that for $\frac{1}{2}+0 \rightarrow \frac{1}{2}+0$ reactions the effect of the nuclear scattering is to decrease the magnitude of the in-plane polarization by a factor $(1-A_y^2)^{1/2}$ and to rotate the polarization vector by an angle β, both of which are independent of the incident direction ϕ. Explicitly, one expects

$$\epsilon_{\rm FPP} = P_0 \mathcal{A}_{\rm FPP}(1-A_y^2)^{1/2}\sin(\phi-\Phi)\,, \tag{4}$$

where $\epsilon_{\rm FPP}$ is the yield asymmetry between protons scattered up and down in the FPP, and

$$\Phi \equiv \theta_{\rm lab}-\beta-\alpha\,. \tag{5}$$

One sees from Eq. (4) that by measuring $\epsilon_{\rm FPP}$ for several values of ϕ, at a scattering angle where $A_y \approx 0$, a value for $\mathcal{A}_{\rm FPP}$ can be extracted directly. At 188.9 MeV, A_y was found to have a zero crossing near $\theta_{\rm lab} = 24.85°$. The dependence of the measured FPP asymmetry (normalized to P_0) on ϕ at this energy and angle is illustrated in Fig. 1, and indicates a value of $\mathcal{A}_{\rm FPP} = 0.483 \pm 0.010$. This is in excellent agreement with earlier determinations of $\mathcal{A}_{\rm FPP}$ for the normal (vertical) polarization component at this energy [14], $\mathcal{A}_{\rm FPP} = 0.471 \pm 0.006$. The observed energy dependence of $\mathcal{A}_{\rm FPP}$ (a very gradual and approximately linear falloff with decreasing energy) was also similar for the sideways and normal polarization measurements [14].

This same technique was then used to obtain precise measurements of $D_{LL'}$ and $D_{LS'}$ at 188.9 MeV, at angles where optical model calculations [15] suggest that A_y should approach $+1$, and hence $D_{LL'}$ and $D_{LS'}$ become small. If we recast Eq. (4) in terms of these observables, we find

$$\epsilon_{\rm FPP} = P_0 \mathcal{A}_{\rm FPP}[D_{LL'}\sin(\phi+\alpha)+D_{LS'}\cos(\phi+\alpha)]\,. \tag{6}$$

With $\mathcal{A}_{\rm FPP}$ determined via the procedure outlined above, we thus have a direct relationship between the measured asymmetries and the spin observables of interest in terms of the known quantities P_0, ϕ, and α for each run. Complete sets of measurements, each involving three or more ϕ settings, were performed at $\theta_{\rm lab} = 16.3°$, 17.3°, and 18.3° ($\theta_{\rm c.m.} = 17.9°$, 19.0°, and 20.1°, respectively), which span the region where A_y achieves its maximum value at this energy. The normalized asymmetries measured at one angle, $\theta_{\rm lab} = 17.3°$, are shown in Fig. 2.

Our final results obtained at these three angles for $D_{LL'}$ and $D_{LS'}$, and hence A_y via application of Eq. (3), are presented in Fig. 3 and in Table I. In the figure, the dashed circles indicate contours of $A_y = 0.98$, 0.99, 0.995, and 0.999 as one moves towards the origin. The solid lines are meant only to guide the eye. The most interesting case occurs at $\theta_{\rm lab} = 17.3° \pm 0.3°$, where we conclude $A_y = 0.99963^{+0.00021}_{-0.00030}$. The quoted error includes both statistical uncertainties and our best estimates of various systematic error contributions, though, as will be shown below, the statistical error dominates at this angle.

We have also taken data of similar quality at three angles for $T_p \approx 200$ and 180 MeV. Though the analysis will

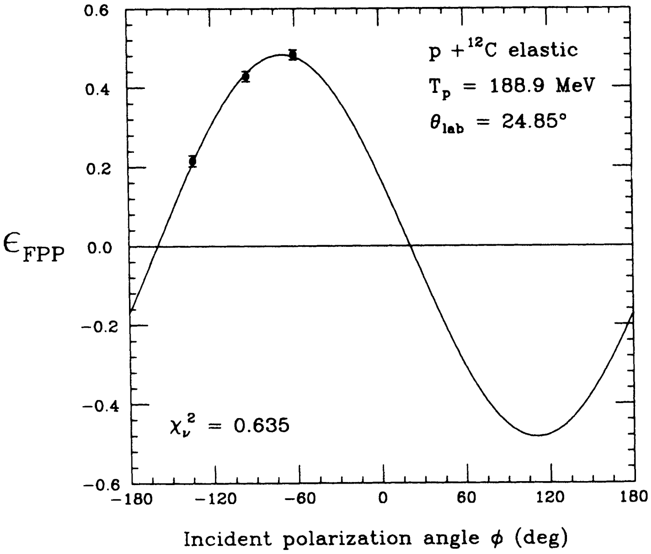

FIG. 1. Measured asymmetries (normalized against P_0) for vertical scattering in the focal plane polarimeter as a function of the in-plane incident polarization angle ϕ. The solid curve is the result of a two-parameter sinusoidal fit [see Eq. (4)] for which the reduced χ^2 is indicated. At this scattering angle, $|A_y| < 0.05$, and the asymmetry amplitude $\approx \mathcal{A}_{\rm FPP}$.

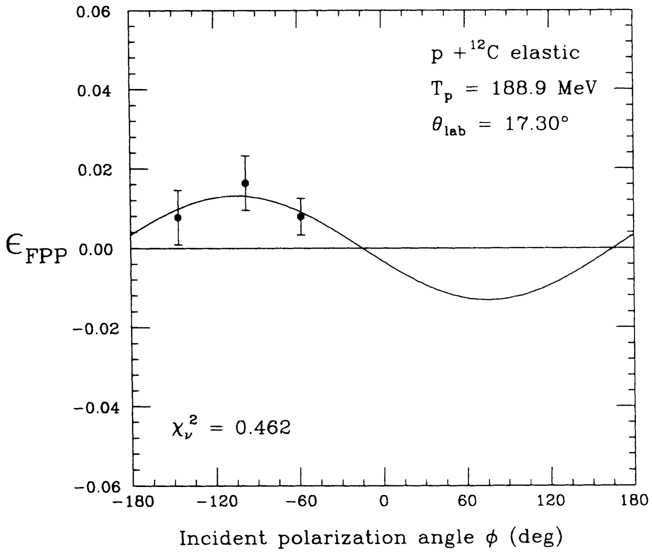

FIG. 2. Same as Fig. 1, but at a scattering angle where A_y is very close to 1. The asymmetry amplitude equals $\mathcal{A}_{\rm FPP}(1-A_y^2)^{1/2}$.

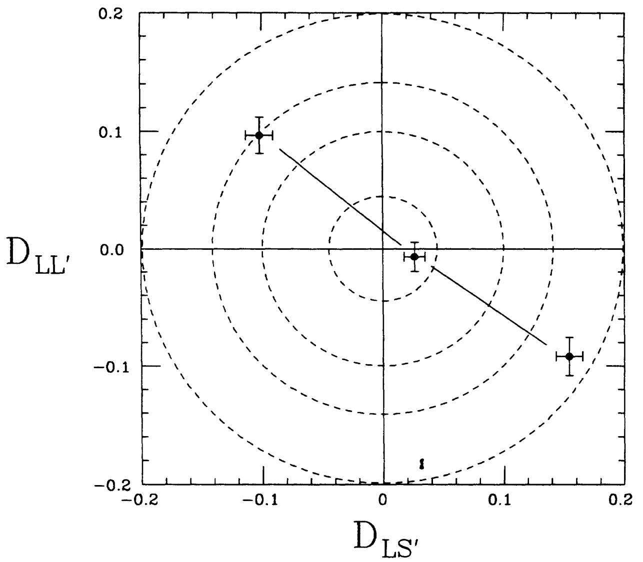

FIG. 3. Results of $D_{LL'}$ and $D_{LS'}$ measurements for $p+{}^{12}C$ elastic scattering at 188.9 MeV. The value of θ_{lab} increases as one moves down and to the right. The solid lines serve only to guide the eye. The dashed circles indicate contours of $A_y = 0.98$, 0.99, 0.995, and 0.999 as one moves towards the origin.

TABLE I. Spin observables measured for $p+{}^{12}C$ elastic scattering at 188.9 MeV. All angles have an uncertainty of ±0.3°.

θ_{lab}	$\theta_{c.m.}$	$D_{LL'}$	$D_{LS'}$	A_y
16.3°	17.9°	0.096 ± 0.015	-0.102 ± 0.011	$0.9901^{+0.0016}_{-0.0017}$
17.3°	19.0°	-0.007 ± 0.013	0.026 ± 0.009	$0.9996^{+0.0002}_{-0.0003}$
18.3°	20.1°	-0.092 ± 0.016	0.154 ± 0.011	$0.9837^{+0.0020}_{-0.0022}$

be more complicated (due to various technical problems encountered during data acquisition), preliminary results suggest that the 200-MeV points lie on a locus approximately parallel to that of the 189-MeV data but displaced upward (as displayed in Fig. 3), while the 180-MeV locus is displaced downward. These trends are in complete agreement with our optical model predictions [15], based on fits to $p+{}^{12}C$ elastic scattering cross section and analyzing power data between $T_p = 160$ and 250 MeV. Because the energy dependence is smooth, continuity arguments [16] require that at an energy somewhat below 189 MeV the locus of $D_{LL'}$ and $D_{LS'}$ values will cross the origin; at that energy (near 188 MeV) there will necessarily be an angle (near $\theta_{c.m.} = 18.9°$) at which A_y is identically equal to 1.

Determinations of absolute analyzing powers require careful treatment of systematic errors, a subject we will treat only briefly in this Rapid Communication. Many potential sources of error have already been discussed in the text.

We have assumed no systematic error in the subtraction of background (negligible) or in peak sum extraction from the K600 spectra. To the extent that the incident proton beam can be characterized by $|P_\uparrow| = |P_\downarrow|$, i.e., exact spin reversal at the polarized ion source, then the FPP functions as a double-arm polarimeter. The FPP vertical scattering asymmetry is defined by

$$\epsilon_{FPP} = \frac{r-1}{r+1}, \quad r \equiv \left[\frac{D_\uparrow U_\downarrow}{D_\downarrow U_\uparrow} \right]^{1/2} \tag{7}$$

(where $D_\uparrow$ is the downward scattered FPP yield for protons leaving the ion source with spin "up," etc.), and is thus insensitive to all orders to purely spin-dependent effects, such as electronic dead times, integrated charge, and target thickness (due to spatial inhomogeneities in the target foil correlated with a spin dependence in the beam position). The asymmetry is also sensitive only in second order to differences in the incident polarization magnitude, any offset in the calculated FPP scattering angle, or any spin-independent inconsistency in the manner in which up and down scattering yields are extracted. Detailed calibration studies [14] for the normal (vertical) polarization, however, have shown no evidence for any such false asymmetries in this device. We estimate the contribution of all these effects to A_y to be less than 1×10^{-5}.

Statistical uncertainties in the incident proton polarization parameters P_0 and ϕ have been propagated in the usual way. Errors in P_0 due to an absolute normalization uncertainty in the high-energy polarimeters (~3%) have negligible effect as $D_{LL'}$ and $D_{LS'}$ go to zero, and contribute about 3×10^{-5} to the error in the A_y value at 17.3°. The uncertainty in A_{FPP} is comparable. As A_y decreases from unity, however, these normalization errors increase and become the dominant source of systematic error.

From Eqs. (4)–(6) one can see that errors in the angles α, β, and θ_{lab} will result in correlated errors in $D_{LL'}$ and $D_{LS'}$, but will have no effect on the value deduced for A_y. Similarly, any *systematic* shift in ϕ (due, for example, to incorrect bend angle information for a dipole magnet) leaves A_y unchanged.

Errors in the quoted values of T_p and θ_{lab} have no effect on the measured value of A_y directly, but render the results less useful for calibration purposes. A potentially very dangerous error would arise from small changes in the angle of incidence of the proton beam on the target. If the angle were the same for all ϕ, this would result only in a miscalculation of θ_{lab}; on the other hand, if the incident beam angle were correlated with ϕ (due, for example, to trajectory changes induced by the precession solenoids), then the FPP asymmetries would have been measured at slightly different scattering angles, and their information cannot be combined. We are currently investigating means of detecting and correcting for this problem, which may have occurred during portions of our 180- and 200-MeV data collection. At 189 MeV we saw no evidence for this correlation, but assume an absolute angle uncertainty of ±0.3° to account for possible beam wander between the angle calibration tests and actual data acquisition.

In summary, we have employed horizontally polarized proton beams and an efficient focal plane polarimeter to determine absolute analyzing powers at intermediate energies, with greatly reduced sensitivity to both statistical limitations and systematic error contributions. The most significant result was obtained at $T_p = 188.9$

±0.3 MeV and $\theta_{\mathrm{lab}} = 17.3 \pm 0.3°$, where we find $A_y = 0.99963^{+0.00021}_{-0.00030}$. Our eventual goal for this work is to map out a region in scattering angle and bombarding energy over which A_y is known absolutely to within several tenths of a percent. This information could then be used to cross calibrate other devices, e.g., to compare the asymmetries observed in a polarimeter to those measured simultaneously in a high resolution device.

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