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Spin dependence in *pp* scattering in the Coulomb-nuclear interference region

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The analyzing power $A_y(\theta)$ for *pp* elastic scattering at 185.4 MeV has been measured with a new technique in which the polarized beam in a storage ring was scattered from an internal H_2 gas target. The measurement covered the angular range $\theta_{c.m.}=5.45°-21.36°$, where A_y is dominated by interference between Coulomb and nuclear amplitudes. It is found that electromagnetic spin-orbit effects are required to explain the data. The present measurement demonstrates for the first time the feasibility and the advantages of nuclear physics experiments with polarized beams in storage rings.

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It is well known that spin-dependent forces (tensor and spin-orbit interactions) represent an important part of the nucleon-nucleon (*NN*) interaction. Relatively small changes in the spin-dependent potentials can have surprisingly large effects in nuclear structure calculations. For example, the predicted binding energy of the three-nucleon system is quite sensitive to the details of the *NN* tensor force. Since the *NN* force is of central importance to all of nuclear physics, it is essential to determine experimentally the details of the internucleon force, and, in particular, its spin dependence.

The advent of storage rings has opened up new possibilities for the study of the *NN* interaction. In this paper, we report an experiment in which the spin dependence of the *pp* interaction was studied using a new experimental technique: a polarized proton beam is accumulated in a storage ring and is scattered from a thin hydrogen target (located inside the storage ring) produced by a hydrogen gas jet. The advantage of this arrangement over conventional scattering experiments is that it is possible to cleanly observe *pp* scattering at angles as small as 2° in the laboratory. This has made it possible to obtain measurements in the angular region where the Coulomb and nuclear amplitudes are comparable in magnitude, which means that the measurements are sensitive to the absolute phase of nuclear scattering amplitudes. We find that the new measurements are consistent with predictions from existing *NN* potential models and phase-shift sets, provided that one includes the effect of the very weak spin-dependent electromagnetic forces that arise from the magnetic moments of the protons.

The experiment made use of a 185.4 ± 0.3 MeV electron cooled, polarized proton beam at the Indiana University storage ring, which is referred to as the "Cooler" [1]. The proton energy was chosen in part because in this energy region the spin-dependent forces are at a relative maximum compared to central forces, and in part for technical reasons because it avoids the need to accelerate the stored beam after accumulation.

The target and detector were similar to that described in a recent paper by Meyer *et al.* [2]. The internal target was a hydrogen jet formed by expansion of gas from a nozzle at 40 K. Approximately 60% of the target was within ± 1 cm of the jet center. The detector system (Fig. 1) consisted of a set of wire chambers and scintillation counters to detect forward-scattered protons in the angular range 2° to 12°. Silicon strip detectors were mounted to the left and right of the beam axis, 10 cm from the beam, to detect recoil protons. Each recoil detector consisted of a pair of 4×6-cm^2 and 300-μm-thick silicon wafers, which provided a coverage in azimuthal angle of $\pm 30°$ (see Fig. 1) [3]. Electronic noise from nearby turbomolecular pumps was eliminated by enclosing the detectors in a Faraday cage, which had a front face of 81% transmittance tungsten mesh.

The forward protons exited the vacuum system through a 127-μm stainless-steel window. The detector (Fig. 1) consisted of a thin plastic scintillator (F) divided into four segments, two pairs of multiwire proportional chambers (WC 1, WC 2), located 105 and 160 cm from the target, respectively, and a 10-cm-thick scintillator (E) divided into octants [2]. Events for which at least one F scintillator, one E scintillator, and one silicon detector responded were stored for later analysis.

The Cooler operated in a cyclic mode, with each 4.9 s cycle consisting of beam injection from the cyclotron (0.5 s), electron cooling (1.0 s), and data acquisition (3.4 s). During injection and cooling, the gas jet was turned off to reduce beam loss by scattering. Injection made use of beam "stacking," i.e., small energy changes and cooling were used to add injected beam to the stack in the ring, making use of the available longitudinal phase space. The beam was accumulated from one cycle to the next. The circulating beam current reached an equilibrium, where the rate of transferred beam equals the loss caused by the target and by residual gas scattering, after about 10 min. The beam intensity at equilibrium is determined by the transfer rate and by the beam lifetime (about 200 s) in the presence of the target. The long time needed to reach equilibrium makes it impractical to reverse the beam polarization rapidly. Thus the measurements were divided into half-hour runs, with roughly equal time with beam polarization up and down.

The data were analyzed event by event. For each event, the analysis was based on the recorded energy ($T1$) deposited in the E detector by the forward proton, the energy ($T2$) deposited in a silicon detector by the recoil proton, the time (t) between the arrival of the two protons at their detectors, and the location of the particle intercepts at the four wire planes. An intercept, by definition, was a cluster of up to four adjacent responding wires. The location of the intercept was taken to be the center of the cluster of the responding wires.

An event was accepted if it satisfied the following conditions. The wire chamber pattern had to fall into one of three categories: exactly one intercept (cluster) in each of the four chambers (class 1, 91.4%), up to three clusters in one or two planes, and one cluster in the remaining two planes (class 2, 5.4%), or one cluster in each of three planes with no cluster in the fourth plane (class 3, 3.2%). For the forward proton, the angle θ and the intercept coordinates x,y at the E detector were deduced from the wire chamber coordinates, except for class 3, where use was made, in addition, of the known target location. The reconstructed track has to coincide with the F and E segments that actually fired. Furthermore, θ and $T2$ had to be consistent with the locus expected from pp kinematics ("L-gate," area a in Fig. 2), the time t had to be consistent with a coincidence ("t-gate," 40 ns wide), the energy of the forward proton had to have the appropriate value ("$T1$-gate"), and the x,y coordinate had to be consistent with the azimuthal acceptance of the recoil detector ("xy-gate").

Accepted events were sorted into 0.4° bins of laboratory scattering angle θ. For each bin, the asymmetry was deduced from about 45 pairs of runs with spin up and spin down, using the cross-ratio method to reduce the effects of instrumental asymmetries due to the differing polarizations of the two spin states of the beam, and instrumental asymmetries in the measuring apparatus [4]. The polarization of the beam was measured with a polarimeter utilizing p-C scattering [5]. The deviation of the polarization of each spin state from the average polarization was mea-

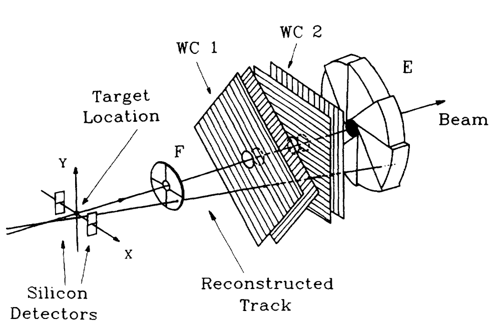

FIG. 1. Schematic diagram of the apparatus used in this measurement. The scintillator arrays are labeled F and E, and the wire chambers are labeled WC 1 and WC 2.

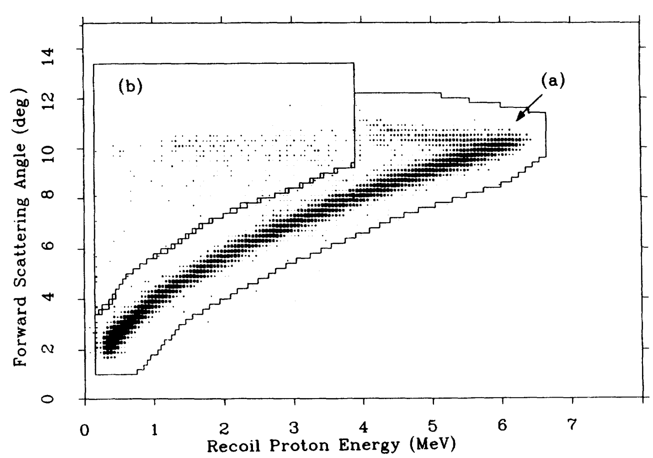

FIG. 2. Response of the detector system to 185-MeV elastic pp scattering. The vertical axis is the forward-scattering angle, and the horizontal axis is the kinetic energy of the recoil proton. The size of the dot corresponds to the logarithmic density of events in a given energy-angle bin. The two enclosed areas are the sorting gates used in the analysis (see text). Note that the silicon detector is too thin to stop the recoil protons resulting from scattering at angles greater than 10°.

sured to be 0.05 or less. The instrumental asymmetry of the detector was determined from the difference in the asymmetry for each spin state and angle bin, and this asymmetry was found to be less than 0.05. The combined effects of both the instrumental asymmetry and the beam polarization difference are conservatively calculated to contribute a negligible error of $\delta(A_y)=1\times10^{-4}$ or less to the quoted errors of our measurement.

The experimental angular resolution arises from multiple scattering (exit foil, detectors, air) and from the finite wire spacing. Monte Carlo calculations showed that the angular resolution function is a Gaussian with 1.2° full width at half maximum (FWHM). A corresponding small (less than $\Delta A_y=0.003$) angle-dependent correction was applied to the measured A_y.

The results of the experiment are not sensitive to details of the analysis procedure. This was demonstrated by repeating the analysis after changing one condition at a time, and recalculating χ^2 between the results before and after the change. It was found that omitting the *xy*-gate, doubling the width of the *T*1-gate, and narrowing the *t*-gate to 20 ns, narrowing the *L*-gate around the kinematic locus by a factor of 2, made only a small change in the results [$\Delta(\chi^2)$ between 0.01 and 0.19].

About 5% of the events were rejected because they fell outside the kinematic locus. The analysis of off-locus events (area *b* in Fig. 2) yielded values of A_y consistent with the on-locus events ($\chi^2=1.02$). An analogous procedure with events outside the *T*1-gate yielded $\chi^2=0.98$. This indicated that the rejected events consist mostly of *pp*-scattering events that were misplaced because of energy losses in the detectors by nuclear reactions, or because the recoil protons were intercepted by the grid in front of the silicon detectors. We conclude that the effect of background upon the final result is negligible.

The measured *pp* asymmetries were normalized to a previously determined calibration of the *pp* analyzing power $A_{y,\mathrm{cal}}(\theta_{\mathrm{cal}})$. This procedure removes any sensitivity to a possible time variation of the beam polarization, since the angular acceptance of the detectors was not changed during the measurement. This calibration [6], which was carried out at 183.1 ± 0.4-MeV proton energy and a laboratory angle $\theta_{\mathrm{cal}}=8.6°$, yielded a value $A_{y,\mathrm{cal}}=0.2122 \pm 0.0017$. The 2.3-MeV energy difference between the calibration and the present experiment was taken into account by applying a correction of $\delta A_y=+0.0011$/MeV, based on a *pp* phase-shift analysis [7]. The normalization made use of the present measurements in the angular range $\theta_{\mathrm{lab}}=7.8°-10.2°$, assuming that A_y is linear in angle. This assumption is justified to an accuracy of $\delta A_y=0.0001$ by the linearity of A_y calculated from phase-shift analyses and *pp*-potential models, as well as a linearity test of the present data.

The result for $A_y(\theta)$ after normalization and correction is shown in Fig. 3. The errors shown include the statistical error ($\delta A_y=\pm 0.005-0.006$), as well as systematic uncertainties ($\delta A_y=0.003-0.004$). The estimate of systematic errors is derived from the χ^2 tests listed above, and from an angle uncertainty caused by a ±5-mm positioning error of the wire chambers. The overall scale factor uncertainty of $\delta A_y/A_y=1.4\%$ is not included.

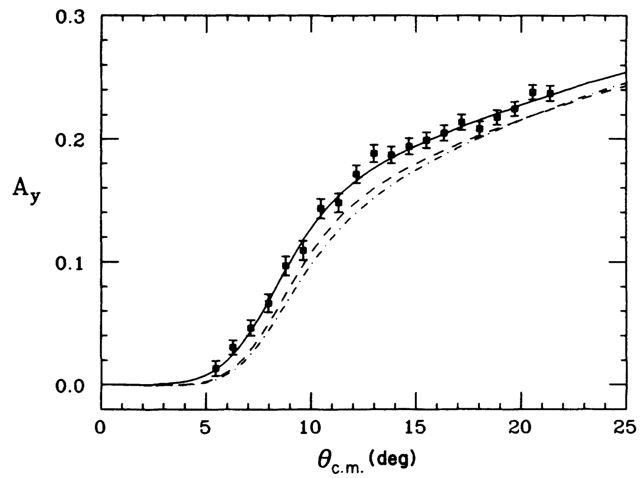

FIG. 3. Results of this measurement, normalized to a precise determination of A_y at $\theta_{\mathrm{c.m.}}=18.1°$. The solid line is the Nijmegen potential result, and the dot-dashed line is the same calculation without the magnetic moment effect [14]. The dashed curve is the prediction of the Paris potential generated by the Paris group [15].

A detailed comparison of the present data with predictions from various phase-shift and *pp*-potential analyses will be published separately [8]. Here we wish to point out only an interesting observation concerning the influence of the proton magnetic moment on the analyzing power in forward-angle *pp* scattering. In neutron scattering from heavy nuclei, significant neutron polarization, arising from the interaction between the neutron magnetic moment and the magnetic field, caused by the motion of the nuclear charge relative to the neutron, was predicted by Schwinger ("Mott-Schwinger" scattering) [9]. The effect was detected, e.g., in the small-angle of 100-MeV neutrons from uranium [10]. For *pp* scattering, the magnetic moment interaction is often neglected, since it is thought to be small compared to the Coulomb interaction. However, some workers have emphasized the importance of the proper treatment of the Coulomb interaction, including the small effects due to the magnetic moment interaction and vacuum polarization [11]. In particular, recent precision experiments of the analyzing power in *np* scattering and *pp* scattering have pointed to the need to include the magnetic moment interaction [12,13].

Figure 3 illustrates the relatively large effects which magnetic moment scattering contributes to the forward-angle analyzing power in *pp* scattering. The solid line shows the prediction based on the Nijmegen nucleon-nucleon potential, which gives an excellent representation of the present data (χ^2/d.f. $=0.5$) [14]. The Paris potential prediction, shown as the dashed curve, appears to fail, in that the predicted analyzing power is systematically too low, but we note that these calculations do not include magnetic moment effects [15]. Both calculations were furnished by the respective theoretical groups. A calculation based on the Nijmegen potential, in which the magnetic moment effects are omitted, is drawn as a dot-dashed line in Fig. 3 [14]. The calculation shows that for angles near $\theta_{\mathrm{c.m.}}=10°$, about $\frac{1}{5}$ of the analyzing power is caused by the magnetic scattering, and so, at the present level of accuracy, it is essential to take these effects into account. The results also suggest that addition of the magnetic moment scattering to the Paris potential calculations will significantly improve agreement with the present measurements.

We first became aware of the large magnetic moment effects because our calculations for the Paris and the Bonn potentials using the program SAID differed from the results supplied to us by the Paris and Bonn groups. It may thus be useful to point out that SAID includes magnetic moment scattering, while the calculations by the Paris and Bonn groups do not.

In summary, the present experiment provides new, accurate data on the spin dependence in *pp* scattering at small angles where Coulomb and nuclear amplitudes are similar in magnitude. It is shown that a significant fraction of the analyzing power is caused by Mott-Schwinger scattering, an effect that is often neglected in *pp*-potential model calculations.

The present experiment is noteworthy as a first demonstration that measurements in storage rings with circulating polarized beams are feasible. We plan to extend the technique to measurements in which the internal target is polarized as well. With internal targets of hydrogen, deuterium, or ^{3}He of thickness 10^{13}–10^{14} atoms/cm^2, the achievable luminosity will be competitive with conventional spin-correlation measurements, but the thin target, the purity of the target, the absence of large magnets, and the large vector and tensor polarization achievable with deuterium atomic-beam sources will offer interesting new opportunities [16].

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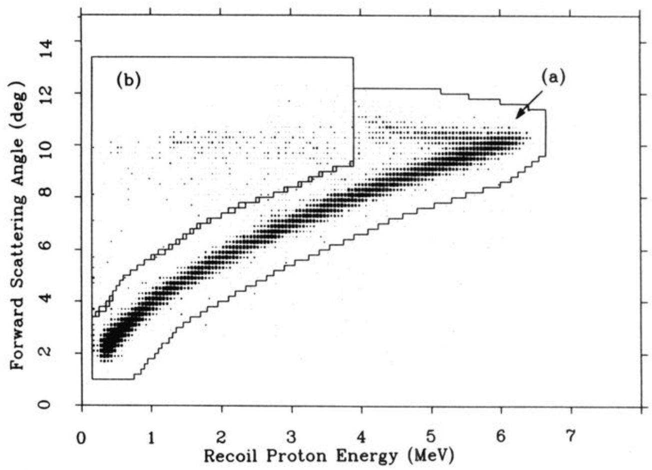

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