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Comparison of analyzing power predictions for *pp* scattering in the Coulomb-nuclear interference region at 185.4 MeV

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Recent measurements of the analyzing power A_y for elastic proton-proton scattering are compared to predictions of phase-shift analyses and potential models. One measurement is an absolute determination of A_y at a beam energy of 183.1 MeV. The second measurement is a precise determination of the angular distribution $A_y(\theta)$ over the angular range $\theta_{\mathrm{c.m.}}=5.45°–21.36°$ at a beam energy of 185.4 MeV. At these small angles the interference between the Coulomb and nuclear amplitudes dominates $A_y(\theta)$. Potential model calculations without the electromagnetic spin-orbit force fail to reproduce the data. Phase-shift analyses, all of which include some form of the electromagnetic spin-orbit force, tend to have a better overall agreement with the data than the potential models.

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Over 50 years of experimental and theoretical effort has been devoted to the study of proton-proton (*pp*) scattering. In spite of this effort, there are still surprising effects, which result from increasingly sophisticated analyses and experiments. One recent example has been the new value of the uncharged pion nucleon couping constant f_p^2, which resulted from a recent phase-shift analysis of 0–350-MeV *pp* scattering [1]. The disagreement between this new determination of f_p^2 and the charged pion coupling constant f_c^2 led to new phase-shift analyses of both the πN and $p\bar{p}\rightarrow n\bar{n}$ systems, with the result that the new determination of f_c^2 was found to be about 7% smaller than the old value [2,3]. There is still a need for precise experiments to accurately determine the *pp* interaction. The energy region around 200 MeV, in particular, includes few precise *pp* polarization data. There are few measurements forward of $\theta_{\mathrm{c.m.}}=10°$, and they are characterized by large statistical uncertainties of $\Delta A_y/A_y=25\%$ or more [4–6]. There are now two new measurements of the analyzing power A_y for elastic proton-proton (*pp*) scattering at a nominal beam energy of 185 MeV. One measurement determined an accurate absolute value of $A_y=0.2122\pm0.0017$ at a scattering angle of $\theta_{\mathrm{c.m.}}=18.1°$ and a beam energy of 183.1 MeV [7]. The other experiment, carried out at the Indiana University Cyclotron Facility (IUCF) "Cooler" storage ring, was a precise measurement of the angular distribution $A_y(\theta)$ in the Coulomb-nuclear interference region at 185.4 MeV [8]. In this paper I present a comparison of the data from these two experiments to calculations of *pp* scattering using both potential models and phase-shift analyses.

The results of the $A_y(\theta)$ measurement are shown in Fig. 1 and listed in Table I [8]. The estimated error in the angle determination has been absorbed into the error estimate of A_y. The normalization of the data is determined from the absolute measurement of $A_y(18.1°)=0.2122\pm0.0017$ at a beam energy of 183.1 MeV [7]. The range of the angular distribution measurement is $\theta_{\mathrm{c.m.}}=5.45°–21.36°$, and extends throughout the Coulomb-nuclear interference region. In this region the magnitude of the Coulomb amplitude becomes comparable to that of the nuclear amplitude and the polarization observables are very sensitive to the interference of the Coulomb and nuclear amplitudes [9]. Additional electromagnetic effects must also be included for a quantitative description. The magnetic moment of the protons, for example, generates a spin-orbit force, which contributes to A_y. This electromagnetic spin-orbit force is gen-

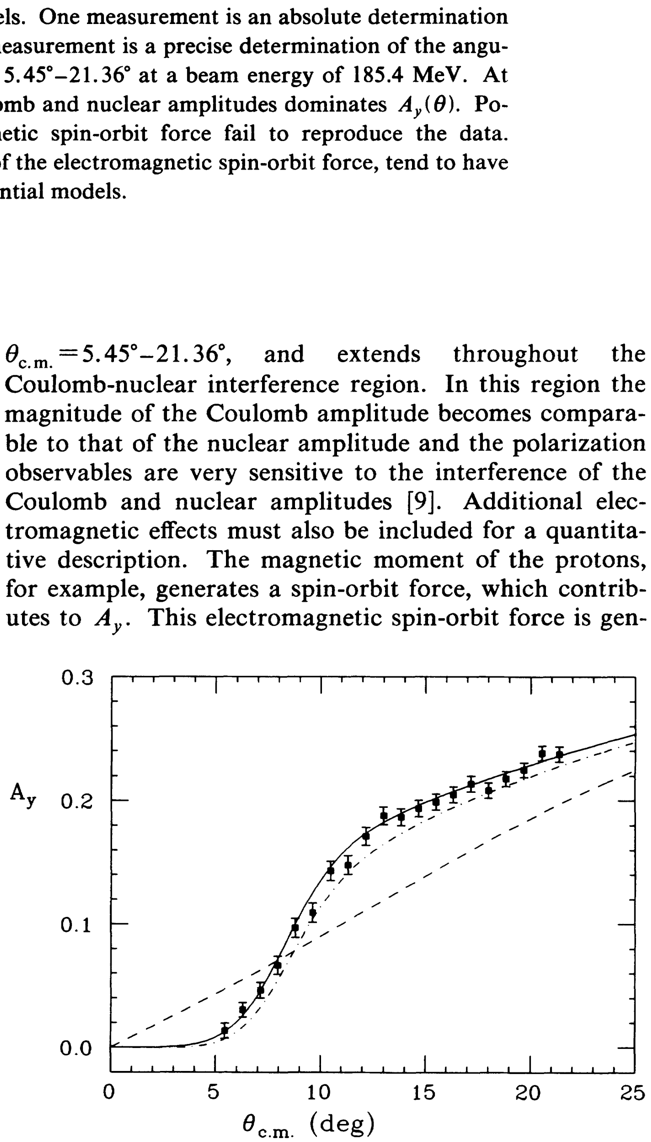

FIG. 1. Results of the new measurements. The normalization uncertainty of $A_y(18.1°)$ is $\Delta(A_y)=\pm0.0017$ [7]. The overall normalization uncertainty of the data at other angles is $\Delta A_y/A_y=1.4\%$. The curves are calculations using the VPI VL40 phase-shift analysis and the SAID program [14]. This analysis is generated using all data from 0 to 350 MeV, and includes the precise normalization point at $\theta_{\mathrm{c.m.}}=18.1°$. The solid curve includes both the nuclear and electromagnetic scattering, while the dashed curve includes only the nuclear scattering. The dot-dashed curve includes both the nuclear and electromagnetic scattering, but not the scattering due to the magnetic-moment interaction.

TABLE I. $A_y(\theta)$ at 185.4 MeV. The normalization of the data is derived from an absolute measurement [7] at $\theta_{\mathrm{c.m.}}=18.1°$. The error in the angle determination has been absorbed into the error of $A_y(\theta)$.

$\theta_{\mathrm{c.m.}}$	$A_y(\theta)$
5.45°	0.0134±0.0061
6.29°	0.0305±0.0058
7.13°	0.0463±0.0064
7.97°	0.0666±0.0073
8.80°	0.0968±0.0077
9.64°	0.1092±0.0079
10.48°	0.1432±0.0078
11.32°	0.1479±0.0076
12.16°	0.1711±0.0073
12.99°	0.1879±0.0071
13.83°	0.1868±0.0069
14.67°	0.1937±0.0067
15.51°	0.1989±0.0065
16.34°	0.2048±0.0064
17.18°	0.2135±0.0063
18.02°	0.2081±0.0061
18.85°	0.2176±0.0060
19.69°	0.2248±0.0059
20.53°	0.2382±0.0058
21.36°	0.2373±0.0061

erated by the interaction of the magnetic moment of one proton with the electric field of the other. The interaction is most familiar in neutron scattering from heavy nuclei, where it generates the Mott-Schwinger polarization observed in small-angle scattering [10,11]. The magnetic-moment interaction has often been ignored or poorly approximated in calculations of *pp* scattering, since it is much smaller than the direct Coulomb interaction. Stoks and de Swart [12] find, however, that it is necessary to include this additional electromagnetic effect for a successful treatment of precise $A_y(\theta)$ data at 50 MeV [13].

The SAID program can be used to calculate the effects of both and direct Coulomb and electromagnetic spin-orbit force upon *pp* scattering [14]. Illustrative calculations with the Virginia Polytechnic Institute (VPI) VL40 phase-shift analysis are shown in Fig. 1. This particular analysis includes data from 0 to 350 MeV and includes the accurate $A_y(18.1°)$ normalization point [7]. The solid curve is the full calculation with all electromagnetic and nuclear scattering included. The dashed line shows the effect of neglecting the Coulomb scattering. The dot-dashed line includes both the Coulomb and nuclear interactions, but the magnetic moment of the proton has been set to zero to eliminate the magnetic-moment scattering. The resulting $A_y(\theta)$ distribution then has a small but significant shift from the full treatment of all scattering forces.

The detailed comparison of the data to the different analyses is carried out using a χ^2 test. The 20 data points of the angular distribution measurement [8] are allowed to have a floating normalization during this test so as to compare the *shape* of the predicted analyzing power, χ^2_{shape}. The comparison of the normalization of a given calculation to the absolute measurement [7] at $\theta_{\mathrm{c.m.}}=18.1°$ is listed as χ^2_{norm}. It is necessary to correct for the different bombarding energy of the angular distribution and absolute normalization data. The energy dependence of the VPI local energy (179–225 MeV) C200 phase shift solution is used to correct for a small energy dependence of $A_y(18.1°)$, resulting in a determination of $A_y(18.1°)=0.2149\pm0.0017$ at 185.4 MeV. The error estimate includes both the overall normalization uncertainty and the uncertainty in the beam energies of both measurements. The resulting normalization uncertainty away from $\theta=18.1°$ is then $\Delta(A_y)/A_y=1.4\%$ after propagation of the normalization errors. The total χ^2, χ^2_{sum}, is then the sum of these two contributions.

Comparison to potential models. —The results of the new measurements have been compared to predictions of the Paris [15], Bonn [16], and Nijmegen [17] potentials. Each calculation was furnished by the group that generated the original potential model. The SAID program can also be used to calculate values of A_y derived from various potential models. The calculations from the SAID program are not potential model calculations, but are instead an interpolation of phase shifts, which are furnished only at some few discrete energies [18]. Evaluation of the origin of disagreements between the SAID potential model calculations and the data would then be a complex task. It was decided that a comparison of potential model calculations to precise data was best achieved using calculations furnished by the original theoretical groups.

The results of the comparison are listed in Table II and plotted in the upper portion of Fig. 2. The Nijmegen potential calculation has the best agreement with the data ($\chi^2_{\mathrm{sum}}=10.4$). The difference between the data and the Nijmegen potential is plotted in the top portion of Fig. 2, where the horizontal line at zero represents the Nijmegen calculation. This excellent agreement is lost if the magnetic moment interaction is omitted (solid curve). The shape and magnitude of $A_y(\theta)$ both change, with a resulting $\chi^2_{\mathrm{sum}}=141$ with respect to the data. The deviation of the Bonn and Paris calculations from the Nijmegen potential are shown as the dot-dashed (Bonn) and dashed (Paris) curves. The resulting χ^2_{sum} is 129 for the Bonn and 87.0 for the Paris calculations. Neither the Paris nor the Bonn calculations include the magnetic moment scattering, and it is likely that this effect accounts for the poor agreement of these two calculations with both the data and the Nijmegen calculations. A comparison of the goodness of the potentials thus requires the same treatment of the electromagnetic effects for the different potentials. Stoks and de Swart have calculated $A_y(\theta)$ at 50 MeV for the Nijmegen, Paris, and Bonn potentials using

TABLE II. Comparison of the potential models.

Model	χ^2_{norm}	χ^2_{shape}	χ^2_{sum}
Nijmegen	0.42	10.0	10.4
Nijmegen (magnetic moment omitted)	63.0	78.0	141
Bonn	79.9	49.4	129
Paris	46.6	40.4	87.0

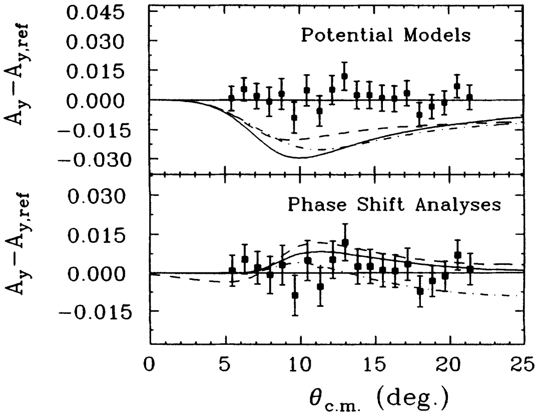

FIG. 2. Results of the new measurements. All results are plotted as their deviation from the Nijmegen potential, which is the zero of each portion of the plot. The upper portion of the plot shows the predictions of the Nijmegen potential if the magnetic moment scattering is neglected (solid curve) and the predictions of the Paris (dashed curve) and Bonn (dot-dashed curve) groups. The lower portion of the plot shows the predictions of the VPI VL35 (solid curve) and C200 (dot-dashed curve) phase-shift analyses. The dashed curve is the prediction of the Saclay S260 phase-shift analysis.

the same treatment of the electromagnetic interaction for all potentials [12]. The Nijmegen and Paris potentials were found to have the best agreement with the precise 50-MeV data set of Smyrski *et al.*[13].

Comparison to phase-shift analysis. —The results of the new measurements have been compared to the most current versions of the VPI C200 (single energy, 179–225 MeV) and VL35 (global, 0–350 MeV) [14], Nijmegen (0–350 MeV) [1], and Saclay S260 (150–450 MeV) [19] phase-shift analyses. The Nijmegen and Saclary analyses have been supplied by the Nijmegen and Saclay groups, respectively, while the VL35 and C200 solutions have been generated using the SAID program [14]. The differences between these calculations and the Nijmegen potential are plotted in the bottom portion of Fig. 2, where the Nijmegen potential is again chosen as the zero level. The VL35 solution (solid line) is practically identical to the Nijmegen analysis (not shown), while the Saclay S260 solution (dashed line) has nearly the same shape but differs primarily in magnitude. The C200 solution is the dot-dashed curve. The χ^2 results are listed in Table III. Not all of the analyses have an assigned error, and the tabulated χ^2 in Table III is calculated only with respect to the central value of each analysis. The excellent agreement of the Nijmegen and VPI phase shifts with the data indicates that the electromagnetic spin-orbit effects are properly included. It has been explicitly shown by Stoks and de Swart that the different treatments of the magnetic moment interaction used by the VPI and Nijmegen groups give equivalent results [20]. It is difficult to reach a definite conclusion concerning the Saclay analysis, however, due to the different energy range of the input data.

TABLE III. Comparison of the phase-shift analyses.

Analysis	χ^2_{norm}	χ^2_{shape}	χ^2_{sum}
VPI VL35	7.3	11.9	19.2
Saclay S260	14.2	15.5	29.7
Nijmegen	7.01	13.2	20.2
VPI C200	8.31	13.4	21.7

It is possible to include new data into the SAID program and generate new phase shifts and errors for the single energy solutions. The influence of both the normalization point and the angular distribution data upon the phases and mixing parameters of the C200 solution is much smaller than the quoted error of the solution and illustrates the constraints imposed by the large *pp* data set. The quoted errors of A_y are reduced by approximately 50% with the inclusion of the normalization point, however, showing that the particular combination of phases which makes up A_y is more precisely determined.

In conclusion, the Nijmegen potential, which has the most complete description of electromagnetic effects, has the best agreement with these data ($\chi^2_{\mathrm{sum}}=10.4$). The neglect of the magnetic moment interaction is shown to generate a large change in $A_y(\theta)$ ($\chi^2_{\mathrm{sum}}=141$). The neglect of this interaction by the Paris and Bonn groups is the likely explanation for the large discrepancy between these calculations and the data. The magnetic moment interaction must be included for a precise comparison of these potentials in the Coulomb-nuclear interference region. Phase-shift analyses tend to be in better internal agreement, presumably due in large part to the more consistent treatment of the magnetic-moment scattering.

It is interesting to consider the effects of the tensor force which must also be generated by the magnetic moment interaction. Calculations using SAID show that the relative effect of the magnetic moment upon the spin correlation C_{nn} at forward angles is greater than the influence of the electromagnetic spin-orbit force upon A_y. The measurement of this effect would require an internal polarized target in the Cooler. The target would consist of a source of polarized hydrogen atoms filling a storage cell, which is a thin-walled cell open on the beam axis to the circulating beam [21]. A development experiment now shows that such measurements are feasible at the Cooler [22], and it is likely that the future experimental program at the Cooler will include the measurement of spin correlations in the Coulomb-nuclear interference region.

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[1] J. R. Bergervoet, P. C. van Campen, R. A. M. Klomp, J.-L. de Kok, T. A. Rijken, V. G. J. Stoks, and J. J. de Swart, Phys. Rev. C **41**, 1435 (1990).

[2] R. A. Arndt, Z. Li, L. D. Roper, and R. L. Workman, Phys. Rev. Lett. **65**, 157 (1990).

[3] R. G. E. Timmermans, Th. A. Rijken, and J. J. de Swart, Phys. Rev. Lett. **67**, 1074 (1991).

[4] A. E. Taylor, E. Wood, and L. Bird, Nucl. Phys. **16**, 320 (1960).

[5] J. N. Palmieri, A. M. Cormack, N. F. Ramsey, and R. Wilson, Ann. Phys. (N.Y.) **5**, 299 (1958).

[6] J. F. Marshall, C. N. Brown, and F. Lobkowicz, Phys. Rev. **150**, 1119 (1966).

[7] B. von Przewoski *et al.*, Phys. Rev. C **44**, 44 (1991).

[8] W. K. Pitts *et al.*, Phys. Rev. C **45**, R1 (1991).

[9] C. Lechanoine, F. Lehar, F. Perrot, and P. Winternitz, Nuovo Cimento **56A**, 201 (1980).

[10] J. Schwinger, Phys. Rev. **73**, 407 (1948).

[11] R. G. P. Voss and R. Wilson, Philos. Mag. **1**, 175 (1956).

[12] V. G. J. Stoks and J. J. de Swart, Nucl. Phys. **A514**, 309 (1990).

[13] J. Smyrski *et al.*, Nucl. Phys. **A501**, 319 (1989).

[14] R. A. Arndt, John S. Hyslop III, and L. David Roper, Phys. Rev. D **35**, 128 (1987); and program SAID (Scattering Analysis Interactive Dial-Up), Virginia Polytechnic Institute, Blacksburg, VA 24061.

[15] M. LaCombe, B. Loiseau, J. M. Richard, R. Vinh Mau, J. Côté, P. Pirès, and R. de Tourreil, Phys. Rev. C **21**, 861 (1980); R. Vinh Mau, private communication.

[16] J. Haidenbauer and K. Holinde, Phys. Rev. C **40**, 2465 (1989); J. Haidenbauer, private communication.

[17] M. M. Nagels, T. A. Rijken, and J. J. de Swart, Phys. Rev. D **17**, 768 (1978); V. G. J. Stoks, private communication.

[18] R. A. Arndt, private communication.

[19] J. Bystricky, C. Lechanoine-Leluc, and F. Lehar, J. Phys. (Paris) **48**, 199 (1987); C. Leluc, private communication.

[20] V. G. J. Stoks and J. J. de Swart, Phys. Rev. C **42**, 1235 (1990).

[21] W. Haeberli, in *Particle and Nuclear Physics (Rockport, Maine, 1988),* Proceedings of the Third Conference on Intersections Between Particle and Nuclear Physics, A.I.P. Conf. Proc. No. 176, edited by Gerry M. Bruce (AIP, New York, 1988), p. 346.

[22] W. Haeberli *et al.*, IUCF Scientific and Technical report, 1991, p. 157.