Polarization in Proton-Proton Scatterings at 735 MeV*

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New measurements by Cheng of p-C polarization as a function of angle and incident proton energy allow us to reduce uncertainty in our previously reported measurement of p-p polarization. On the basis of this new information, it is concluded that the p-p polarization at 735 MeV reaches a maximum of $(60\pm2)\%$.

I. BACKGROUND

We have recently reported measurements of the polarization and differential cross section in proton-proton and proton-nucleus scatterings at 725 MeV.[1] These results were obtained by double elastic scatterings. The energy of the scattered beam was analyzed after the second target with a 102° magnetic spectrometer, which gave a resolution of ±10 MeV. To minimize systematic errors the sense of the first scattering angle was reversed rather than that of the second scattering angle. Also, for experimental simplicity in obtaining polarization data on a variety of materials and scattering angles, the first target and scattering angle (polarizer) were varied while the second scattering angle (analyzer) was fixed at 6°. This experimental method proved quite convenient in most regards. An unfortunate consequence when scattering from hydrogen, however, was the sizeable recoil energy loss at the first target, resulting in arrival of a variable-energy proton at the second target. Results of the polarization in p-p scattering depended on our knowing the analyzing power of carbon at 6° as a function of proton energy (because, as the angle of scattering at the hydrogen target was increased from 4° to 20°, the proton energy at the carbon analyzer dropped from 720 to 600 MeV). The few experimental data available gave a very unclear picture of this energy dependence.[2]

II. RECENT MEASUREMENTS OF THE ANALYZING POWER OF CARBON

Cheng has recently completed measurements of nucleon-nucleon polarization at the 184-in. cyclotron at 700, 600, 500, and 400 MeV.[3] In so doing he found the polarization of protons scattered from carbon by a double-elastic-scattering method. The cyclotron beam was degraded before scattering. The senses of both the first and second scattering angles were reversible. After the first target, a $\pm3\%$ momentum analysis was accomplished by bending magnets. Elastic scatterings after the second target were selected by range telescopes. The p-C polarization at 6° in the laboratory was found by taking the square root of the asymmetry. Cheng's results on p-C polarization at 6° are shown in Fig. 1. What we consider most significant is the smooth, almost linear change of the p-C polarization with energy, in contrast to the apparent large fluctuations that characterize the few earlier measurements.

An extrapolation through Cheng's data gives a value for p-C polarization at 725 MeV that is about 0.035 lower than our measurement. This is nearly 4 standard deviations from the stated errors on the measured values. Although the discrepancy is conceivably real, we believe it much more likely that it is due to some systematic bias. Such a bias can arise from (a) differences in the acceptance of inelastic scattering

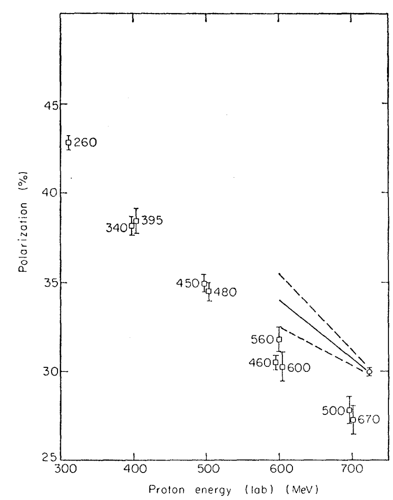

FIG. 1. Polarization versus incident energy for protons on carbon at 6° (laboratory). □—Ref. 3, ○—Ref. 1. The small numbers attached to the points displayed refer to the cutoff energy in the range telescope used in Ref. 3. In addition to the errors quoted, there is a normalization error of less than 0.016 on the points from Ref. 3. The slope of polarization versus energy from Ref. 3 is used to draw the line from our previously measured point at 725 MeV. These values are then used as the analyzing power to interpret the asymmetries of the beam scattering first from protons and then from carbon. The upper and lower dashed lines are the assumed errors, and are used henceforth for error propagation.

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[1] P. G. McManigal, R. D. Eandi, S. N. Kaplan, and B. J. Moyer, Phys. Rev. **137**, B620 (1965).
[2] See Fig. 3 of Ref. 1 for a summary of these results.
[3] David Cheng, Ph.D. thesis, Lawrence Radiation Laboratory Report No. UCRL-11926, 1965 (unpublished); D. Cheng, B. Macdonald, W. Oliver, J. Helland, and P. Ogden, Bull. Am. Phys. Soc. **10**, 717 (1965).

contribution, (b) differences in spatial and momentum distribution of the two beams, and (c) possible systematic scattering-angle misalignments.[4] These errors tend to be independent of or only weakly dependent on proton energy. Were there constant systematic biases in an experimental system leading to asymmetry errors, the effect of such biases would be minimized by using analyzers whose power was measured by the same system. In this way the asymmetry error is shared between polarizer and analyzer—thereby reducing the maximum effect on either. Thus, in order to best interpret our *p-p* polarization data, we normalize the magnitude of the carbon polarization to our carbon point at 725 MeV. We then assume that the possible systematic differences between the two experiments are

TABLE I. Polarization for proton-proton scattering.

θ_{lab} (deg)	Asymmetry from analysis with carbon[a]	Energy at center of carbon analyzer (MeV)	*p-p* polarization based on curve shown on Fig. 1 for A_{p-C} (6°)
4.5	0.075±0.004	718	0.248±0.013
6.0	0.107±0.004	713	0.352±0.014
7.3	0.118±0.003	708	0.387±0.011
8.6	0.129±0.004	703	0.421±0.015
10.0	0.145±0.003	694	0.468±0.013
11.5	0.166±0.004	684	0.530±0.017
13.0	0.172±0.002	674	0.543±0.015
15.3	0.185±0.002	655	0.574±0.018
16.4	0.196±0.004	645	0.602±0.023
18.0	0.198±0.003	631	0.599±0.023
20.5	0.200±0.003	605	0.591±0.027

[a] Ref. 1.

independent of proton energy (since we have no reason for believing in nor grounds for assigning an energy dependence), and use Cheng's data for the variation in the *p*-C analyzing power with energy. On that basis the curve of analyzing power was chosen to be linear, beginning at our previous result of 0.300±0.003 at 725 MeV and increasing by 0.040±0.015 at 600 MeV, as shown in Fig. 1.

III. PROTON-PROTON POLARIZATION

These new values of the analyzing power of carbon allow a recalculation of *p-p* polarization from our previously reported values of asymmetry (produced by scattering first on hydrogen, then at 6° on carbon.) These results are given in Table I and Fig. 2. The uncertainty in the *p-p* polarization due to uncertainty in the analyzing power of carbon is still three times that due to the quoted error in the asymmetry at the larger angles.

The reported energy of 735 MeV was the approximate energy at the first target.

We find a maximum polarization of 0.602±0.023, which is consistent with but slightly higher than the result of Betz *et al.*,[5] 0.560±0.038, and that of Cheng *et al.*[3] at 700 MeV, 0.558±0.016. (Cheng states that there may be additional normalization errors associated with this measurement of ≤0.016.) The difference between Cheng's value and ours is similar to the *p*-C differences discussed above, and is believed to be the result of the same experimental bias.

The general agreement among the above measurements confirms the large, though previously unexpected, proton polarization in this energy region.

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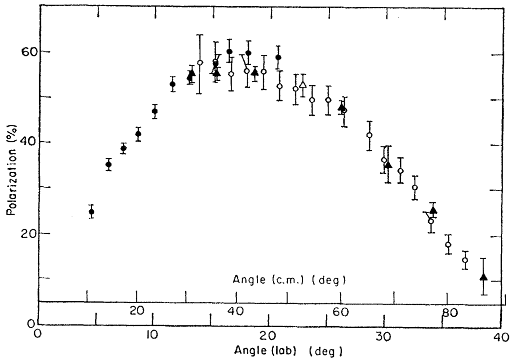

FIG. 2. Polarization versus angle for protons scattered from protons. The errors on our data include the uncertainty in the analyzing power of carbon as shown in Fig. 1, as well as the uncertainty in the asymmetry. The errors on the points from Ref. 4 include the uncertainty of polarization of the polarized target. ●—This paper (735 MeV); ○—Ref. 5 (736 MeV); ▲—Ref. 3 (700 MeV).

[4] It should be pointed out that we would expect these effects to produce much smaller errors for *p-p* scattering since cross sections vary much more slowly with angle, and inelastic events present no experimental problem (Ref. 1).

[5] F. Betz, E. Arens, O. Chamberlain, H. Dost, P. Grannis, M. Hansroul, L. Holloway, C. Schultz, and G. Shapiro, Phys. Rev. **148**, 1289 (1966).