Polarization of Protons Scattered from C^{12}†

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The polarization of protons elastically scattered from carbon in the energy region between 4.65 and 5.0 Mev has been measured by double scattering from carbon targets. These results, together with the findings at Harwell by Evans and Grace, show that the polarizations predicted from the phase shift analysis are somewhat in error. This disagreement may be explained by making small changes in the splitting of the *P*- and *D*-wave phase shifts without seriously affecting the fit to the angular distributions. It was found that in the energy range from 3.0 to 4.0 Mev the *D*-wave phases required from 1° to 4° additional splitting, while in the range from 4.0 to 5.0 Mev the splitting of the *P*-wave phases had to be reduced by 4°. These modified phase shifts give a revised contour map of spin polarization versus energy and angle.

INTRODUCTION

FROM the phase-shift analysis of the elastic scattering of protons from C^{12} by Reich *et al.*,[1] the polarization of the scattered protons has been calculated.[2] Subsequently, the results of these calculations have been used in other experiments where C^{12} was used as an analyzer for proton polarization.[3,4] Since the angular distributions, from which the phase shifts were deduced, are not as sensitive to the spin-orbit splitting of the phase shifts as is the polarization, it is necessary that these calculations be checked experimentally. For this purpose a double scattering experiment has been performed using a carbon polarimeter in the energy region between 4.65 and 5.0 Mev.

This paper will discuss the method employed to measure the spin polarization by the double scattering of protons from C^{12}. The results of these measurements in conjunction with the Harwell results[5] make it possible to obtain a more accurate set of phase shifts and thus a more accurate contour diagram of the

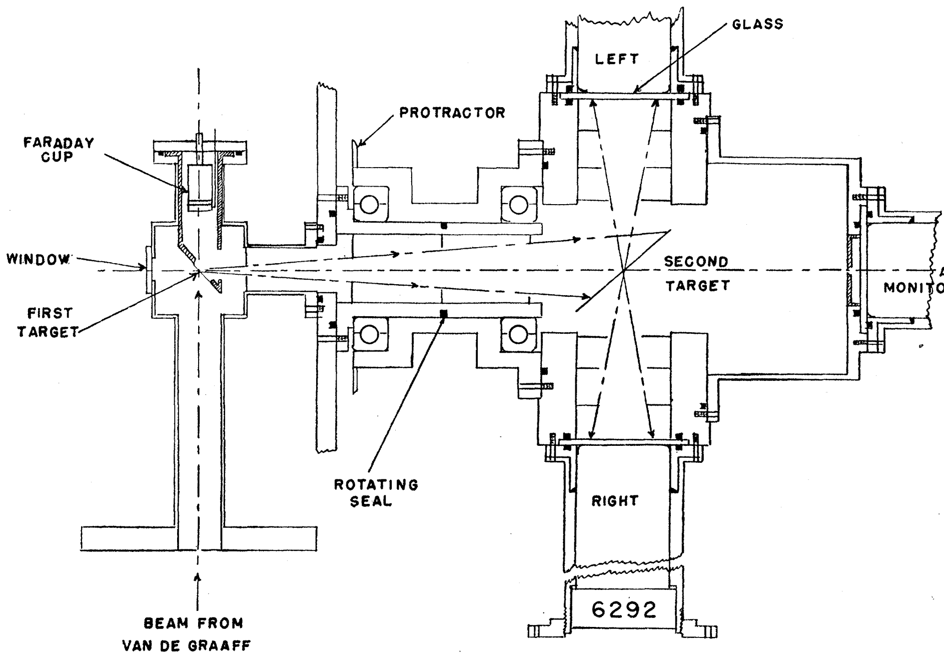

FIG. 1. Construction of the polarimeter showing the two scattering chambers. The second chamber has the second target, monitor detector, and the two asymmetry detectors and may be rotated about the monitor detector axis to allow variation of the azimuthal angle ϕ_2.

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1 C. W. Reich, G. C. Phillips, and J. L. Russell, Jr., Phys. Rev. **104**, 143 (1956).
2 G. C. Phillips and P. D. Miller, Phys. Rev. **115**, 1268 (1959).
3 R. E. Warner and W. P. Alford, Phys. Rev. **114**, 1338 (1959).
4 M. K. Juric and S. D. Cirilov, Phys. Rev. **112**, 1224 (1958).
5 J. E. Evans and M. A. Grace (unpublished).

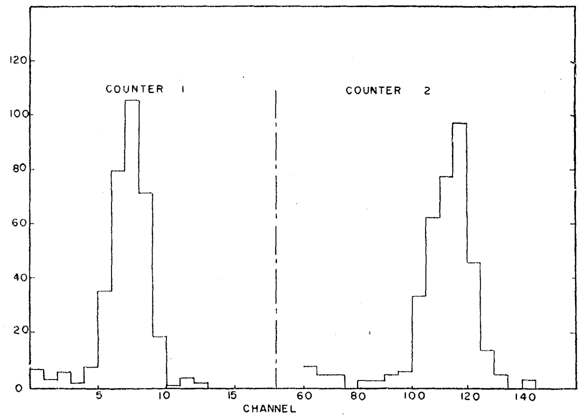

FIG. 2. Typical pulse-height distributions of protons twice scattered from carbon at a bombarding energy of 4.78 Mev.

polarization as a function of the energy and the scattering angle.

THEORY

For the scattering of spin $\frac{1}{2}$ particles from spin zero nuclei the cross section and the polarization are:

$$\sigma(\theta)=(1/k^2)(|f_c|^2+|f_i|^2)$$

and

$$\mathbf{P}(\theta)=\frac{2\,\mathrm{Im}(f_c f_i^*)}{|f_c|^2+|f_i|^2}(\hat{k}_1\times\hat{k}_2).$$

Here θ is the scattering angle in the center-of-mass system, k is the wave number of the incident beam, $\hat{k}_1$ and $\hat{k}_2$ are unit vectors in the direction of the incident and scattered beams, respectively, and f_i and f_c are defined by:

$$f_c=(-\eta/2k)\csc^2(\theta/2)\exp[i\eta\ln\sin^2(\theta/2)+2i\sigma_0]+\sum_{l=0}^{\infty}[(l+1)\exp(i\delta_l^+)\sin\delta_l^+ + l\exp(i\delta_l^-)\sin\delta_l^-]\times P_l(\cos\theta)e^{2i\sigma_l}$$

and

$$f_i=\sum_{l=1}^{\infty}[\exp(i\delta_l^-)\sin\delta_l^- - \exp(i\delta_l^+)\sin\delta_l^+]\times\frac{dP_l(\cos\theta)}{d(\cos\theta)}\sin\theta e^{2i\sigma_l}.$$

In the expressions above $\eta=\mu ZZ'e^2/\hbar^2k$, σ_l is the lth Coulomb phase shift, and the $\delta_l^{\pm}$ are the scattering phase shifts.[1]

If two detectors are placed symmetrically with respect to the direction of the first scattered beam and coplanar with the beam, then the asymmetry in the scattering from the second target is:

$$A=P_1(\theta_1)P_2(\theta_2)\sin\phi_2.$$

$P_1(\theta_1)$ and $P_2(\theta_2)$ are the polarizations resulting in the first and second scatterings and ϕ_2 is the azimuthal angle of the plane of the detectors measured from the plane of the first scattering. Experimentally this asymmetry is:

$$A=(R-L)/(R+L).$$

where R is the counting rate for the counter on the right and L the counting rate for the counter on the left. The first scattering is taken to be to the right.

APPARATUS

The polarimeter and scattering chamber are shown in Fig. 1. The polarimeter is designed so that it is free

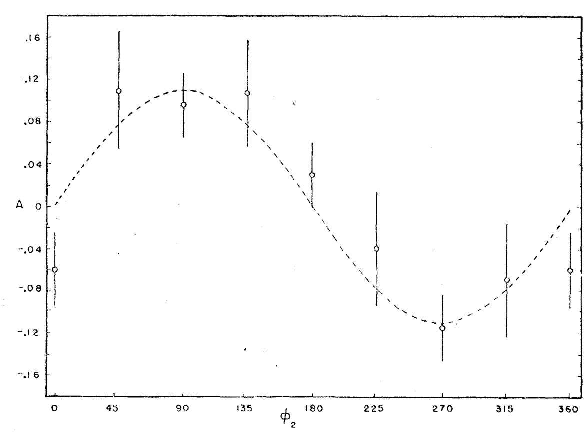

FIG. 3. Azimuthal angular distribution of protons twice scattered from carbon at 4.78-Mev primary energy. The asymmetry ratio A (see text) is plotted versus the azimuthal angle ϕ_2. The dotted curve shows a sinusoidal curve passed through the data points.

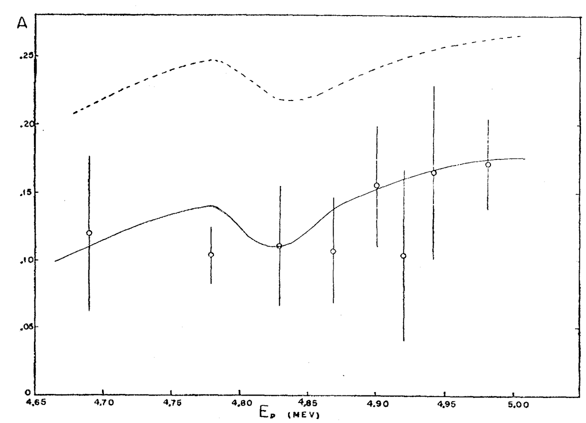

FIG. 4. Variation of the asymmetry ratio, A, versus bombarding energy for the double scattering of protons from carbon at $\theta_1=\theta_2=90°$. The dotted curve is the prediction (see reference 2) of A employing the phase shifts derived by Reich (see reference 1), while the solid curve employs small deviations from those phase shifts (see text).

to rotate about the first scattered beam, in order that differences in counter efficiency may be eliminated. The alignment of the components of the polarimeter is insured by the axial symmetry of recesses machined in the front and rear faces of the center section as is shown in Fig. 1.

The three detectors use CsI(Tl) scintillation crystals with DuMont 6292 photomultipliers. The two asymmetry detectors have large solid angle ($\sim$0.10 steradian) and employ 1.75-inch diameter 0.005-inch thick crystals. The pulses from these detectors were sorted and recorded by a RCL 256 channel pulse-height analyzer and an Atomic Instruments 20 channel analyzer.

ALIGNMENT

In an experiment where an asymmetry is measured, any misalignment can obscure the effect to be measured. The precision construction of the polarimeter insures the correct alignment of its components, so that the only possible misalignment can be in the positioning of either the first target foil or the beam upon the target. The alignment of the target is greatly simplified by the small window in the first scattering chamber. The target holder is put in position with a clear plastic film instead of the target; by sighting through the monitor slit of the polarimeter it can be determined if the center of the target is on the center line of the polarimeter. The beam is then centered on the target by replacing the Faraday cup with a quartz plate and then centering the beam with the target in place.

Another source of possible error is the asymmetry due to the angular distribution of particles over the first scattering solid-angle. At 90° this effect will, in general, be small because the variation of the cross section across the solid-angle is relatively small. However, at more forward angles this effect may become more pronounced and can completely obscure the asymmetry due to the polarization. This fundamental asymmetry cannot be avoided, but its effect may be estimated from the angular distribution data. In the experiment that is described below the errors due to this effect were calculated and found to be $\pm 1\%$,

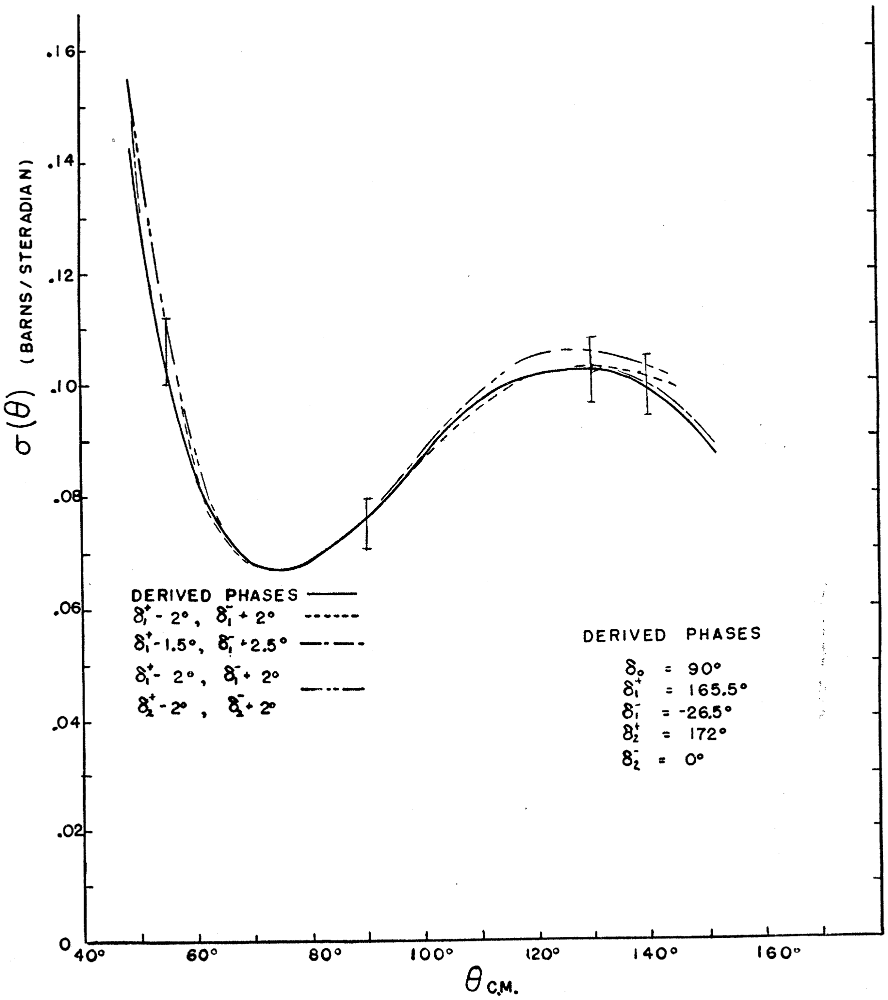

FIG. 5. Reanalysis of the angular distribution at 4.0 Mev. The experimental points of Reich *et al.* of absolute cross section versus center-of-mass scattering angle for $C^{12}(p,p)C^{12}$ are compared to the prediction of the phase shift analysis. The derived values of Reich *et al.* and three deviations from them are shown.

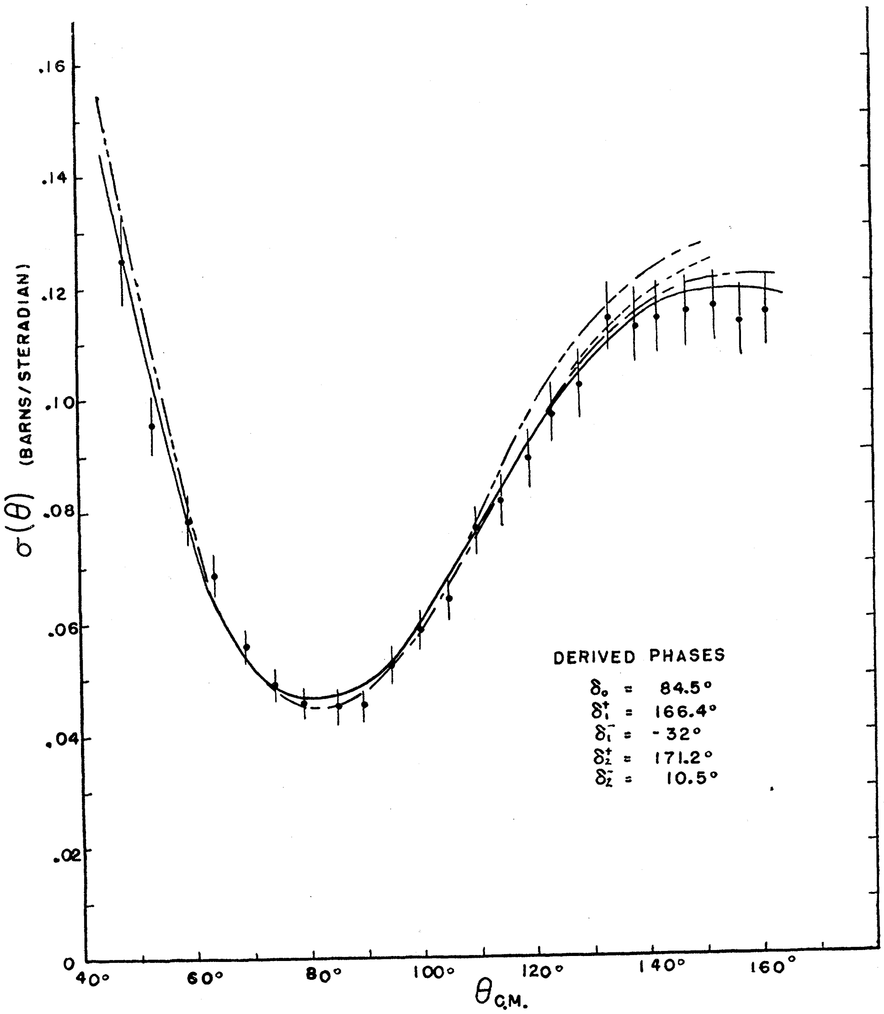

FIG. 6. Reanalysis of the angular distribution at 4.613 Mev. See Fig. 5 for symbols of smooth curves.

which is negligible in comparison with the statistical uncertainty of the data.

EXPERIMENTAL

Both the first and second scatterings take place about 90° (lab). The first target was a carbon foil with a thickness of 1.0 mg/cm^2, while a sheet of 0.00025-inch Mylar was used as the second target. The Rice Institute 5.5-Mev electrostatic accelerator was employed as a source of protons.

The counting rates were very low (about 6 counts per minute for a 2 microampere beam current); but since there was no appreciable background at this energy, the pulses due to the doubly-scattered protons were easily resolved. Typical pulse-height distributions are shown in Fig. 2. After each data point the polarimeter was rotated through 180° and the measurement repeated. No systematic deviation was observed between the two measurements, and in all instances the results agreed to within the statistical uncertainty.

At 4.78-Mev bombarding energy the asymmetry was measured as a function of ϕ_2, and as is shown in Fig. 3, the results show the sinusoidal behavior that is predicted by the theory. The asymmetry was measured as a function of energy for bombarding energies between 4.65 and 5.0 Mev. Since carbon was used for both scatterings, the calculation of the polarization from the measured asymmetry involves two unknown quantities: the polarizations, P_1 and P_2, for the two scatterings. For this reason the predicted polarizations are used to calculate the asymmetry so that the predicted and experimental results might be compared. As seen in Fig. 4 the agreement between the two is good with respect to sign and the general behavior, but is poor with respect to the magnitude of the effect.

CONCLUSIONS

This lack of agreement between the predicted and observed polarizations has also been observed by Grace and Evans at Harwell,[5] who for first scattering at 60°

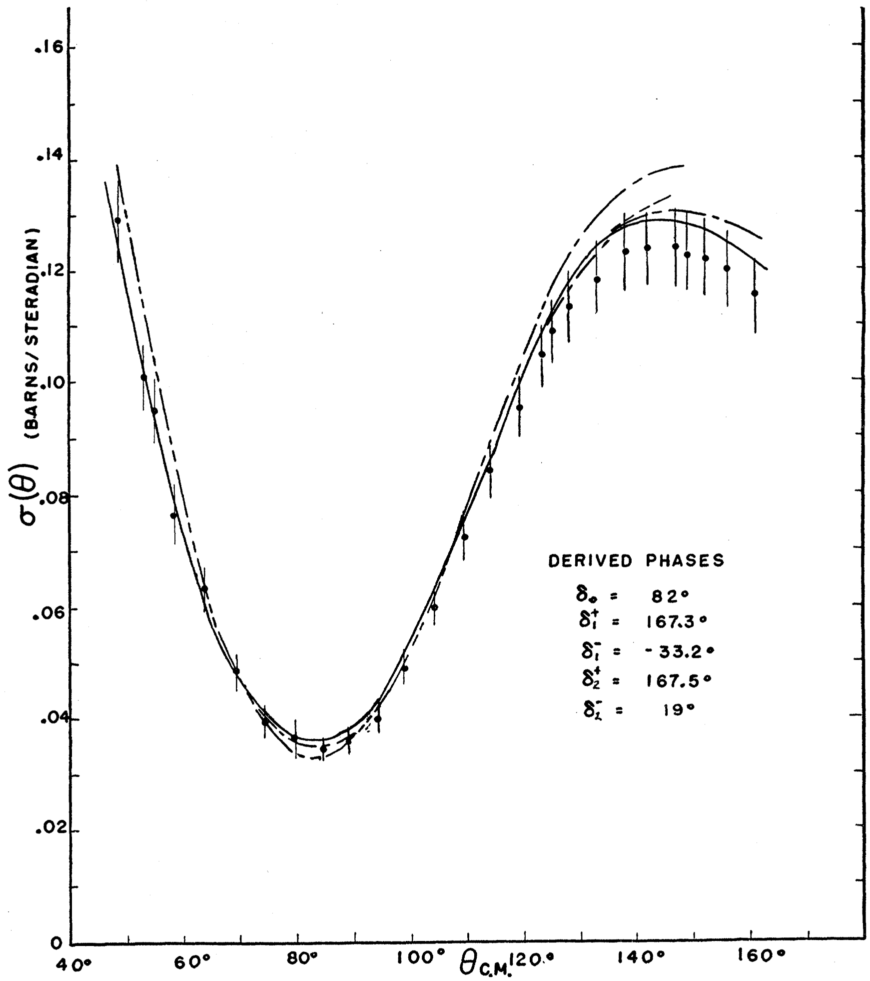

FIG. 7. Reanalysis of the angular distribution at 4.964 Mev. See Fig. 5 for symbols for smooth curves.

have observed that the polarization is about twice the predicted value[2] in the energy range of 3.0 to 4.0 Mev.

Since $P_2'(\cos\theta)$ is zero at 90°, the chief contribution to the polarization at this angle comes from the splitting of the P-wave phase shifts. This is not the case at 60°, where it has been observed that the polarization is insensitive to the P-wave splitting but is strongly dependent on the splitting of the D-wave phase shifts. Because of these two facts it is reasonable to suppose that the observed polarizations, as well as the angular distributions, may be fitted within the experimental accuracy by causing further splitting of the D-wave phase shifts, while at the same time reducing the P-wave splitting.

In the study of the elastic scattering of protons by Reich *et al.*, complete angular distributions were taken at 4.613 and 4.964 Mev.[1] At other energies only excitation curves were taken at several angles. For the purpose of phase shift modification, the complete angular distributions have been reanalyzed to determine how small phase-shift modifications affect the fit to the experimental data.

To explain the data found in this experiment it was necessary to decrease δ_1^+ by 1.5° and increase δ_1^- by 2.5° over the energy range from 4.0 to 5.0 Mev. This modification produces a fit to the angular distributions that is within the experimental and statistical error. These revised fits to the data of Reich *et al.* are shown in Figs. 5, 6, and 7. To fit the angular distributions at 4.613 and 4.964 Mev it was impossible to add any additional D-wave splitting. However, at 4.0 Mev the effect due to decreasing δ_2^+ by 2° and increased δ_2^- by 2° is within the experimental and statistical uncertainty. This is sufficient to explain the Harwell data, if, starting at 3.0 Mev, δ_2^+ is gradually decreased and δ_2^- is gradually increased. From 4.0 to 4.5 Mev this trend is reversed so that the phases return to their derived values at 4.6 Mev. These small phase shift deviations are given on Figs. 5, 6, and 7.

When these modifications are taken into account, the measured polarization asymmetries reported above agree both in magnitude and general behavior with the predicted result, as is shown by the solid curve in Fig. 4. A revised contour map of the polarization is shown

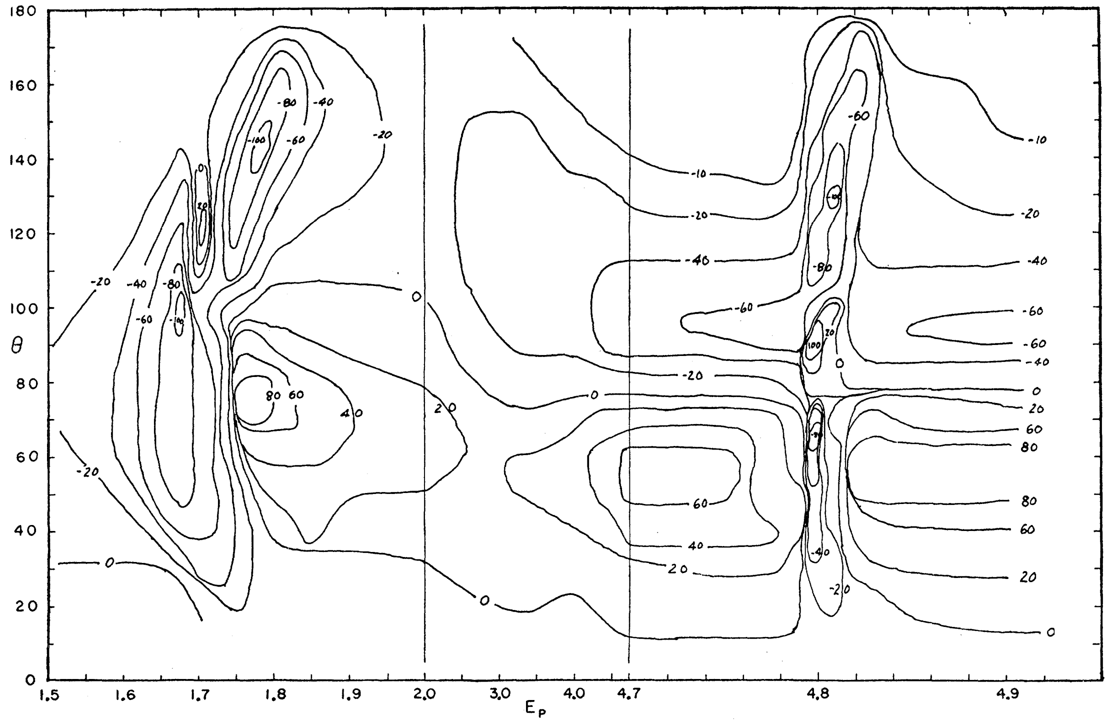

FIG. 8. Contour map of spin polarization for $C^{12}(p,p)C^{12}$. Lines of equal spin polarization are shown versus bombarding energy and center-of-mass angle. This map employs phase shifts modified slightly from those of reference 1 and is to be compared to the earlier map of reference 2. Below 3 Mev the above map and that of reference 2 are supposed to be identical.

in Fig. 8 where the phase shift deviations discussed above have been employed. Caution should be employed in using this map for the determination of spin polarization: although it is believed that the map gives the correct polarization to about $\pm 10\%$ of the indicated values, there still remains the possibility that the phase shifts in certain energy regions are in error due to inaccuracies in the elastic scattering data or to nonuniqueness of the phase shift fit.

It should be noted that only very small phase shift deviations from the earlier values were necessary to produce a reasonable fit to the polarization data without destroying the quality of fit to the angular distributions. Thus the determination of spin polarization from elastic scattering angular distributions requires much greater precision than is usually obtained. However, rather crude polarization measurements provide an extremely sensitive method of determining phase shifts when used in conjunction with the elastic scattering data.