Measurements of polarization in C12(p,p) scattering

Measurements of Polarization in $C^{12}(p,p)$ Scattering

By J. E. EVANS, A.E.R.E., Harwell

1. Introduction

There are two good reasons for investigating the polarization produced in $C^{12}(p,p)$ scattering. One is to provide the data for using C^{12} as an analyser of proton polarization, and in this connection it is worth mentioning that a solid carbon analysing target has several advantages over gaseous helium. These are:

1. A target in the form of a plane sheet allows better geometry than a volume of gas.
2. No energy is lost in target-containing windows.
3. Less energy is lost to the recoiling carbon nucleus than to a helium nucleus. 2 and 3 imply that the final protons are detected in the presence of less background and with better resolution.

The second reason for measuring $C^{12}(p,p)$ polarization is to provide a sensitive check on the accuracy of phase shifts derived from the $C^{12}(p,p)$ angular distribution, and we include an application of this.

2. Experiments with the 5 MV Electrostatic Generator

This work was reported recently. It was done in collaboration with Dr. M. A. GRACE [1][1]. The $C^{12}(p,p)$ polarization was measured at 60° (lab.) in the energy range 2.3–4.3 MeV using helium as an analyser. Figure 1 shows the arrangement used. The self supporting carbon target was made by spraying a suspension of colloidal graphite in alcohol on to a glass slide. The carbon film (2 mg/cm²) was floated off after evaporation of the alcohol.

The CsI crystals used for detecting the protons were milled down to .0025″ in order to minimize the background. The technique for doing this was described [1]. The pulse height spectrum of the observed protons is shown in figure 2.

---

[1] Numbers in brackets refer to References, page 248.
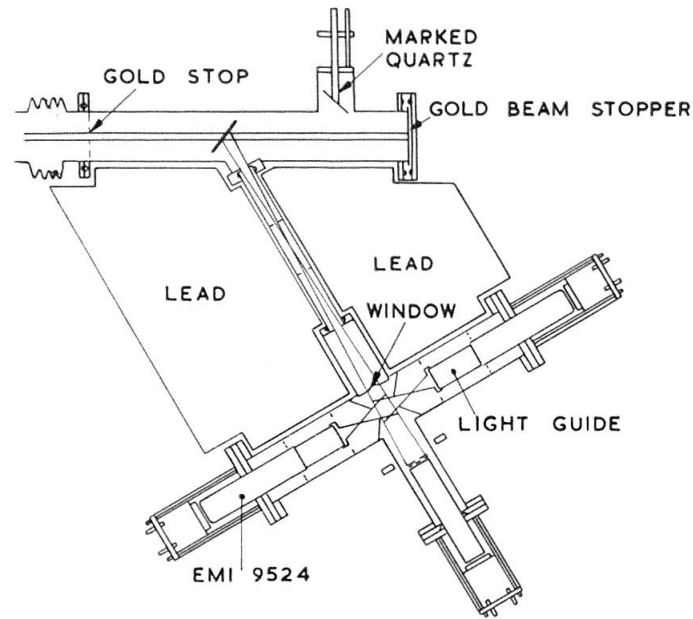
Figure 1

The first scattering chamber and the helium polarimeter
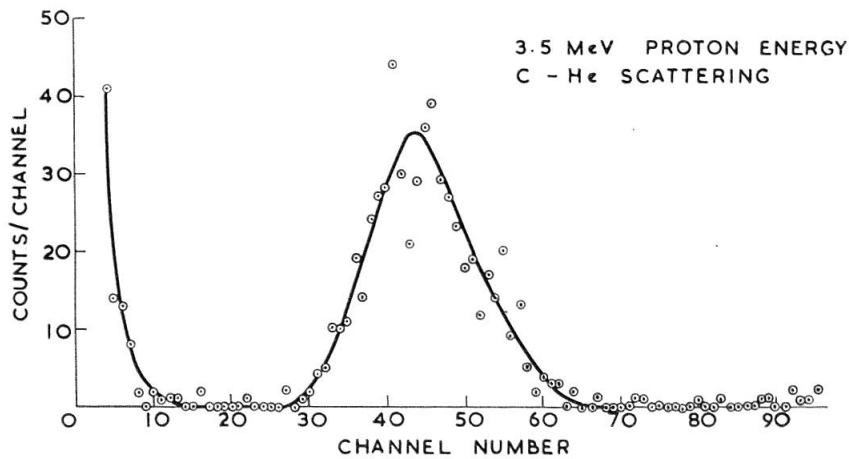
Figure 2

The pulse height spectrum of protons after double scattering from carbon and helium.
The initial energy was 3.5 MeV.

The results for the polarization are shown in figure 3 along with two points obtained by double scattering from C^{12} at 60°. The polarization predicted from a phase shift analysis due to REICH, PHILLIPS and RUSSELL [2] is also shown. In this region the polarization is extremely sensitive to changes in the splitting of the two d-waves, but not to the s- and p-wave phase shifts. A change of 6° in the separation of the two d-wave phases is sufficient to account for the large discrepancy observed

in the polarization at 4 MeV but the corresponding change in the cross section as measured by REICH *et al.* is only of the order of their experimental error. We sent our results to Dr. G. C. PHILLIPS at the Rice Institute who deduced a very similar correction to the phase shifts [3]. Figure 4 shows the effect on the polarization of varying the *d*-wave separation.

Figure 3

Experimental results for C^{12} (p, p) Polarization at 60° (lab.) with the polarization predicted from the phase shift analysis
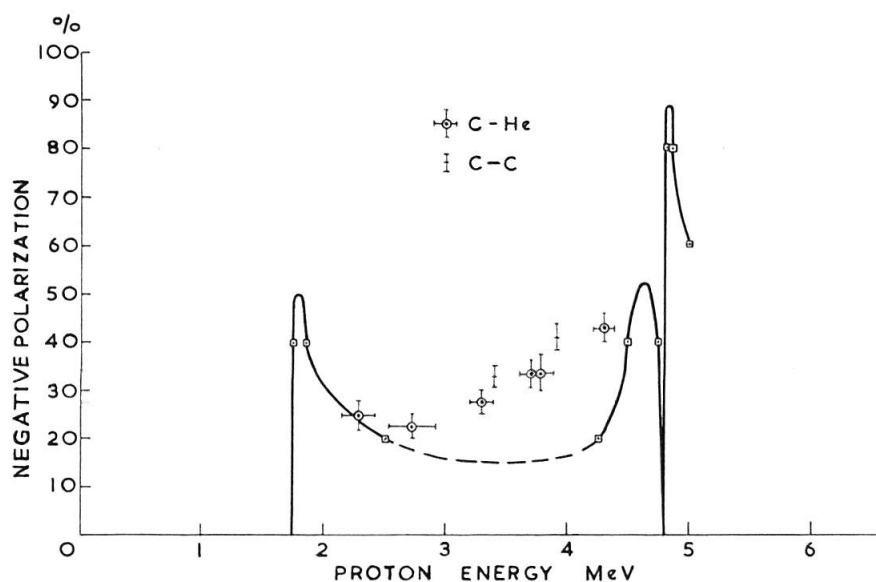
3. Experiments with the 12 MV Tandem Electrostatic Generator

Dr. J. H. MONTAGUE has collaborated in much of this work which is being done to extend the energy range of the measurements. As a complementary programme Drs. DEARNALEY, MONTAGUE and WHITE-HEAD have made angular distribution measurements of the elastic scattering for a phase shift analysis. A carbon polarimeter has been incorporated in a 30″ scattering tank, after a suggestion by Dr. E. PAUL. It is shown in figure 5. The polarimeter can be rotated from outside the evacuated tank, so that the first scattering angle is continuously variable. Each CsI crystal is suspended within a reflecting enclosure, normal to the surface of the photo-cathode of a 2″ EMI tube. With an arrangement such as in figure 5, the flux of protons striking the first target is perhaps a factor of 10^{14} times the flux of protons being detected. This means that the polarimeter must be screened to prevent protons reaching the detectors by devious paths after being scattered from the walls of the tank.

The energy of the beam from the Tandem Generator was calibrated after scattering from a thin carbon foil into the back counter shown in figure 5. For this purpose we used the results of REICH *et al.* for the scattered intensity near the 4.8 MeV resonance in the elastic scattering. This enabled us to relate the analyser magnet field as measured with a proton resonance magnetometer to the beam energy.

Figure 4

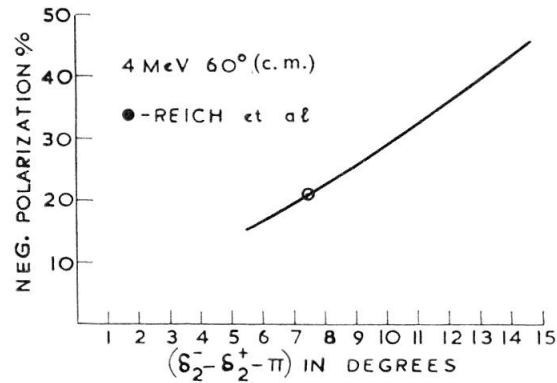$C^{12}(p, p)$ polarization at 4 MeV and 60° (c. m.) as calculated from the phase shifts of REICH (*et al.* [2]) with the *d*-wave splitting varied
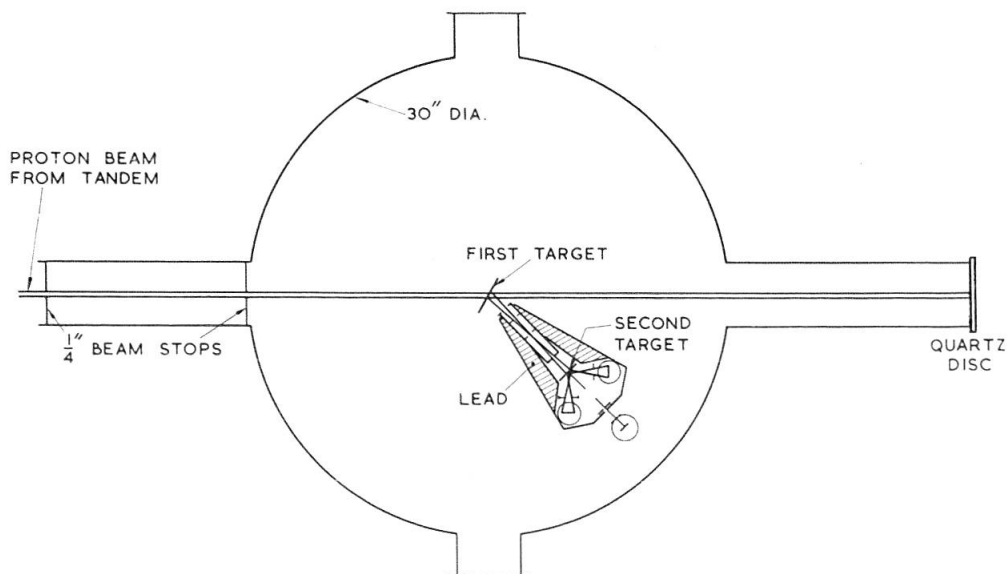

Figure 5

Scattering tank with carbon polarimeter

The most efficient way to use a polarimeter is to incorporate large solid angles so as to keep the counting rate high. The effective polarization P_2 for analysing is then inferred from a calibration in which well-

collimated protons of known polarization P_1 enter the polarimeter, to produce a measured right-left asymmetry. The calibration so obtained remains good for subsequent experiments so long as polarization and cross-section do not vary between the angular limits set by the entrance slit of the polarimeter.

We required accurate values of P_1 in order to calibrate the polarimeter. It is readily seen that the product $P_1 \overline{P_2}$ should be as large as possible for good accuracy. If X is the right-left ratio, then $\delta(P_1 \overline{P_2})/P_1 \overline{P_2} \simeq 2 \, \delta X/X^2$ for $X \gg 1$.

It is known from the work of WARNER and ALFORD [4] carried out with a helium polarimeter, that the polarization in C^{12}(p,p) at 45° (lab.) is very high in the region of 5.5 MeV. We used a different method to check their results and to provide values of P_1 with which to calibrate the polarimeter. This method, which is not new [5] has the advantage of being self-consistent. First, good geometry in the polarimeter was achieved by setting small circular apertures (3/16″) in front of the counters at 1.55 inches from the carbon analysing target. These then defined a mean value of 48° for the second scattering angle. The beam entering the polarimeter was of circular section and well collimated ($\pm\,0.7°$ R.M.S. deviation). Then a good approximation to the angular detector efficiency (in arbitrary units) is given by

$$I(x) = \int\limits_{x-1}^{1} \left[(1 - y^2)\left(1 - \overline{y - x}^2\right)\right]^{1/2} dy$$

where x is proportional to the deviation from 48°. This function was tabulated by the Computer Group and the R.M.S. deviation found to be $\pm\,2.4°$.

Three experiments on double scattering of protons on C^{12} at 48° (lab.) were now performed.

The good geometry made a low counting rate inevitable. With $2\,\mu$A of protons hitting the first target, the counting rate in the depleted detector was about one per minute. The counter resolution however was excellent. The spread in the peak of double scattered protons was $6^1/_2\%$ at half height. The CsI crystals were .010″ thick and the background was negligible.

The mean scattering energies E_1, E_2 for the three experiments were arranged to be

E_1 (MeV)	E_2 (MeV)
5.59	5.16
6.04	5.16
6.04	5.59 .

For the second experiment an aluminium foil was placed between the carbon targets. To ensure that E_1, E_2 were as tabulated, the energy loss in each target was measured using the back counter shown in figure 5, in a subsidiary experiment. A foil support was made which could be moved in front of a gold target placed at the centre of the scattering chamber. Protons were reflected into the back counter which was calibrated by varying the machine energy. Then the carbon targets which had been fixed to the support were moved in turn into the scattered beam and the consequent energy loss measured. The required thickness for the aluminium foil was then calculated and a suitable foil obtained and its thickness confirmed in the same way.

In order to deduce the three polarization products $(P_1 P_2)$ from the experiments it was necessary to take account of the asymmetry due to mechanical inaccuracies in the polarimeter as well as that due to the angular spread of the beam entering the polarimeter. Another subsidiary experiment was done in which a gold target (5 mg/cm²) was used to scatter protons into the polarimeter. These protons are not expected to be polarized [1] so that any difference in the detector counting rates which is not statistical must be due to the asymmetry described above. The effect of the angular spread of the first scattered beam is calculable (see 4 below) and was removed from the counting rate ratio of the two detectors. The amended ratio was found to be 0.97 ± .025 ($\theta_1 = -48°$) and 0.97 ± .025 ($\theta_1 = +48°$) where θ_1 is the first scattering angle. The counter efficiencies were thus taken to be in the ratio of 0.97:1. One can distinguish three separate effects which may determine this ratio.

a) The two detectors may subtend unequal solid angles.
b) The polarimeter carbon target may be non-uniform.
c) The scattering angles set by the two detectors may be unequal.

The three experimental right-left ratios for the carbon double scattering were obtained with the first scattering angle set at +48° and again at − 48°. Each ratio was corrected first using the efficiency ratio of 0.97:1. The products $P_1 P_2$ were then deduced using the formula of 4 below. For this purpose the angular distributions of polarization and cross-section at 5 MeV were taken from the literature [2, 3]. The three products then allowed calculation of the polarization in $C^{12}(p, p)$ at 48° (lab.) at the three different energies tabulated.

So long as asymmetry of type (c) above is not present one expects to find that each product $P_1 P_2$ deduced as described should not depend on the sign of the first scattering angle. In fact no such dependence was found within the counting statistics. It is worth noting that only a special type of asymmetry due to (c) will be revealed by the experiment with a gold first target. (This special type occurs when the rotation

from $-$ 48° to $+$ 48° does not take place about the first target as centre. Our results do not indicate the presence of this special type.) In order to obtain consistent results, it was found necessary to ensure that the beam entering the scattering chamber, did so only after completely filling the 1/4″ apertures. The reason for this is clear when it is realised that at 48° the C^{12} differential scattering cross-section is changing at the rate of 5% per degree so that a misalignment of 1° in the polarimeter produced a 10% effect in the right-left ratio.
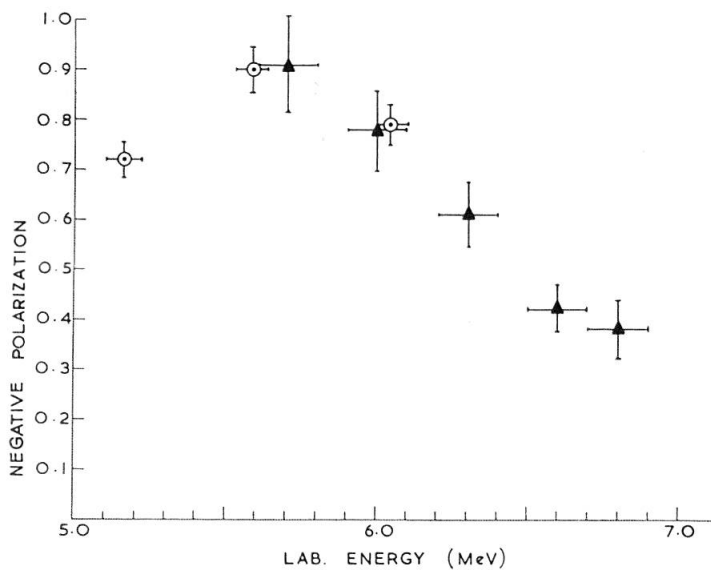

Figure 6

C$^{12}(p, p)$ polarization. The present results at 48° (lab.) are shown as open circles. The full triangles represent the results of WARNER and ALFORD at 45° (lab.).

The effect of the angular spread in the second scattering was examined. If the first scattering geometry is regarded as perfect (apart from the asymmetry effects considered in [4]) then the second polarization as measured is a mean polarization defined by

$$\overline{P}_2 = \frac{\int \sigma_2(\theta_2) \, P_2(\theta_2) \phi(\theta_2) \, d\theta_2}{\int \sigma_2(\theta_2) \phi(\theta_2) \, d\theta_2}$$

where θ_2 is the angle of second scattering and $\phi(\theta_2)$ is the angular detector efficiency introduced earlier. A numerical integration using the forms for $P_2(\theta_2)$ and $\sigma_2(\theta_2)$ in the literature [2, 3] showed however that $\overline{P}_2$ was only 1% less than P_2 (48°). This implied that the three values of the polarization in C$^{12}(p,p)$ at 48° (lab.) as calculated were only $\frac{1}{2}$% low. These values were

Lab. Energy (MeV)	Polarization
6.04	$-0.79 \pm .04$
5.59	$-0.90 \pm .045$
5.16	$-0.72 \pm .036$

They are shown plotted in figure 6 and the results of WARNER and ALFORD at $45° \pm 2.3°$ also plotted for comparison. The experiment we have described does not give the sign of the polarization. We were in no doubt about this however even without the results of WARNER and ALFORD because we had done preliminary experiments with a polarimeter of poor geometry using our earlier results (figure 3) for calibrating the polarimeter. The polarization found was always negative when defined by the vector $\boldsymbol{K}_{in} \times \boldsymbol{K}_{out}$.

The results of figure 6 are now being used for an accurate calibration of the polarimeter, used with poor geometry. Absorber foils will then be used to extend the polarization measurements if possible to the maximum energy available with the Tandem Generator (11.5 MeV).
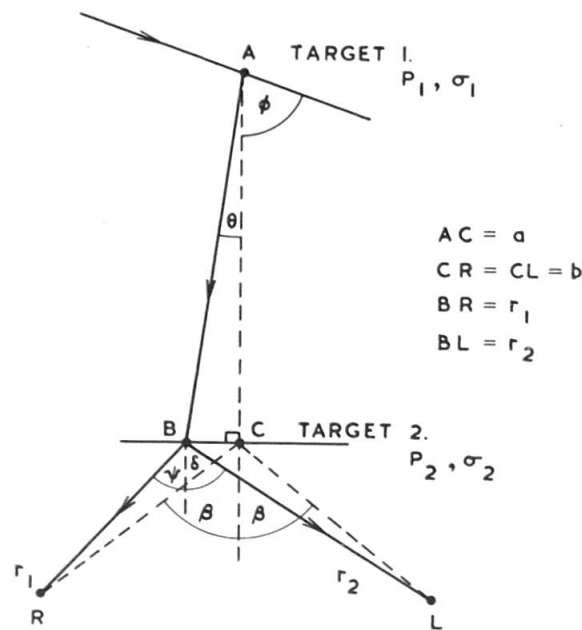
Figure 7

The effects of an extended second target in a double-scattering experiment

4. The Asymmetry due to an Extended Second Target

Figure 7 shows the arrangement of a double scattering experiment. It may be seen that the right/left ratio observed is given by

$$\frac{R}{L} = \frac{\int_{-\theta_1}^{+\theta_1} \sigma_1(\phi+\theta)\,\sigma_2(\psi-\theta)\cdot S(\theta)\cdot \frac{1}{r_1^2}[1+P_1\,(\phi+\theta)\cdot P_2\,(\psi-\theta)]\,d\theta}{\int_{-\theta_1}^{+\theta_1} \sigma_1(\phi+\theta)\,\sigma_2(\delta+\theta)\cdot S(\theta)\cdot \frac{1}{r_2^2}[1-P_1\,(\phi+\theta)\cdot P_2\,(\delta+\theta)]\,d\theta}$$

where $S(\theta)$ is a source term which depends on the shape of the second target. After expanding, this ratio turns out [6] to be as given in figure 8 where σ_1, σ_2, P_1 and P_2 and their derivatives with respect to angle are evaluated at the mean angles set by the apparatus. A calculation which applies to the good geometry experiment described gives for 5 MeV protons.

$$\frac{R}{L} = \frac{1 + 0.022 + P_1 P_2 (1 - 0.011)}{1 + 0.044 - P_1 P_2 (1 + 0.005)} \cdot$$

The parameters were:
$$\begin{aligned} a &= 7.0 \text{ inches} \\ b &= 1.55 \text{ inches} \\ \beta &= 48° \\ \theta_1 &= .027 \text{ radians.} \end{aligned}$$

Figure 8

Effect of an extended second target

$$\frac{R}{L} = \frac{1 + (R+S)\dfrac{\theta_1^2}{n} + P_1 P_2 \left\{ 1 + [(V + PT + QU + R) + (W + QT + UP + S)]\dfrac{\theta_1^2}{n} \right\}}{1 + (R-S)\dfrac{\theta_1^2}{n} - P_1 P_2 \left\{ 1 + [(V + PT + QU + R) - (W + QT + UP + S)]\dfrac{\theta_1^2}{n} \right\}}$$

where $n = 3$ for a rectangular target

$n = 4$ for a circular target

$$P = \frac{\sigma_1'}{\sigma_1}$$

$$Q = 2B \sin \beta - \frac{A\sigma_2'}{\sigma_2}$$

$$R = \frac{A^2}{2}\frac{\sigma_2''}{\sigma_2} - \frac{B^2}{2}\sin 2\beta \frac{\sigma_2'}{\sigma_2} + \frac{\sigma_1''}{2\sigma_1} - B^2 - 2AB \sin \beta \frac{\sigma_2'}{\sigma_2}$$

$$S = \frac{\sigma_1'}{\sigma_1}\left[2B \sin \beta - A\frac{\sigma_2'}{\sigma_2} \right]$$

$$T = \frac{P_1'}{P_1}$$

$$U = -A\frac{P_2'}{P_2}$$

$$V = \frac{A^2}{2}\frac{P_2''}{P_2} - \frac{B^2}{2}\sin 2\beta \frac{P_2'}{P_2} + \frac{P_1''}{2P_1}$$

$$W = -A\frac{P_1'P_2'}{P_1 P_2}$$

and $$A = \frac{a \cos \beta}{b} + 1$$

$$B = \frac{a}{b} \cdot$$

REFERENCES

[1] J. E. EVANS and M. A. GRACE, Nucl. Phys. *15*, 646 (1960).

[2] C. W. REICH, G. C. PHILLIPS, and J. L. RUSSELL, JR., Phys. Rev. *104*, 143 (1956).

[3] T. A. TOMBRELLO, R. BARLOUTAUD, and G. C. PHILLIPS, Submitted for publication in Physical Review.

[4] R. E. WARNER and W. P. ALFORD, Phys. Rev. *114*, 1338 (1959).

[5] M. J. SCOTT, Phys. Rev. *110*, 1398 (1958).

[6] J. E. EVANS, A calculation of the asymmetry due to an extended second target in experiments to determine nuclear spin polarization. A.E.R.E. Report R 3347.