Garwin for helpful conversations and Dr. S. Rosendorff for his cooperation on the appendix. Lastly, we wish to thank the staff of the Nevis cyclotron laboratory for their cooperation.

APPENDIX

Following Foldy's[18] treatment of the magnetic moments, the most general way to introduce an electric dipole moment into the covariant, gauge invariant Hamiltonian for a spin $\frac{1}{2}$ particle interacting with a static electromagnetic field is by the addition of a term $-(ie f\hbar/2mc)\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$.

This term leaves the Hamiltonian invariant under charge conjugation but not under parity or time reversal. It can be written as $+(fe\hbar/m s)\bar{\psi}\{\sigma\cdot\mathbf{E}+i\alpha\cdot\mathbf{B}\}\psi$ so that the Hamiltonian for a muon with an EDM in a constant external magnetic field, $\mathbf{B}$, becomes

$$H = c\alpha\cdot\pi + \beta mc^2 + (ife\hbar/mc)\beta\alpha\cdot\mathbf{B}$$
$$= \rho_1 e\sigma\cdot\pi + \rho_3 mc^2 - (fe\hbar/mc)\rho_2\sigma\cdot\mathbf{B}.$$

Performing a Foldy-Wouthuysen transformation[19,20]

[18] L. I. Foldy, Phys. Rev. 87, 688 (1952).
[19] L. L. Foldy and S. A. Wouthuysen, Phys. Rev. 78, 29 (1950).
[20] H. Mendlowitz and K. M. Case, Phys. Rev. 97, 33 (1955): The transformation used here is identical with that used in this paper for the anomalous magnetic moment. It is interesting that the result is similar, i.e., the EDM as well as the anomalous part of the magnetic moment precesses with a frequency γ times that

gives

$$H' = e^{-i\rho_2\phi/2}He^{i\rho_2\phi/2},$$

where $\tan\phi = -c\sigma\cdot\pi/mc^2$. Dropping terms which connect positive and negative energy states we find for the positive energy part

$$H' = \epsilon_\pi - \left(\frac{e\hbar}{2\epsilon_\pi/c}\right)\sigma\cdot\mathbf{B} + \frac{fe\hbar}{m\epsilon_\pi}\sigma\cdot(\pi\times\mathbf{B}),$$

where $\epsilon_\pi = (m^2c^4+c^2\pi^2)^{\frac{1}{2}}$ and define $\mu_0 = e\hbar/mc$. Replacing ϵ_π by its eigenvalue γmc^2 and noting that $\mathbf{v} = \pi/\gamma m$ gives

$$H' = \epsilon_\pi - (\mu_0/2\gamma)\sigma\cdot\mathbf{B} + f\mu_0\sigma\cdot(\mathbf{v}/c\times\mathbf{B}),$$
$$d\sigma/dt = (i/\hbar)[H',\sigma] = (-\mu_0/\hbar\gamma)\sigma\times\mathbf{B}$$
$$+ (2f\mu_0/\hbar)\sigma\times(1/c)(\mathbf{v}\times\mathbf{B}),$$
$$= \sigma(d\theta/dt)\hat{n}.$$

But $\omega_0 \equiv (\mu_0/\gamma\hbar)B$. So

$$d\theta/dt = 2f(v/c)\gamma\omega_0,$$

and

$$\theta = 2f\theta_0\beta\gamma. \tag{2}$$

of the normal moment. The same result is obtained classically [see V. Bargmann, L. Michel, and V. L. Telegdi, Phys. Rev. Letters 2, 435 (1959)]. Note that the anomalous magnetic moment term has been omitted from H since it gives rise to a precession orthogonal to the EDM precession and is unobservable within the precision of this experiment.

Charge Independence in the Reactions $p+d \to \pi^0+\mathrm{He}^3$ and $p+d \to \pi^+ + \mathrm{H}^3$ at 450 Mev*

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An experiment has been performed to measure the branching ratio in the production of He³ and H³ in p-d collisions at 450 Mev at 140° in the c.m. system. The result is 2.13±0.15 which is in agreement with the prediction of a ratio 2 on the basis of charge independence alone. The production cross sections were found to be $(d\sigma/d\Omega)_{\mathrm{He}^3} = 5.41\pm0.29$ μb/sr and $(d\sigma/d\Omega)_{\mathrm{H}^3} = 11.55\pm0.49$ μb/sr.

INTRODUCTION

SEVERAL workers[1-4] have tested the validity of the hypothesis of charge independence for reactions in-

[1] C. S. Godfrey, Phys. Rev. 96, 1621 (1954); R. A. Schluter, Phys. Rev. 96, 734 (1954); V. B. Fliagin et al., J. Exptl. Theoret. Phys. U. S. S. R. 35, 854 (1959) [translation: Soviet Phys.—JETP 35(8), 592 (1959)]; R. H. Hildebrand, Phys. Rev. 89, 1090 (1953).
[2] K. C. Bandtel, W. J. Frank, and B. J. Moyer, Phys. Rev. 106, 802 (1957).
[3] A. V. Crewe et al., Phys. Rev. Letters 2, 269 (1959).

volving pion production. Only one of these experiments[4] has been performed to an accuracy greater than 10%.

Among suitable reactions[5,6] for this test are

$$p+d \to \mathrm{H}^3+\pi^+,$$

and

$$p+d \to \mathrm{He}^3+\pi^0.$$

The branching ratio for these two reactions is predicted to be 2.

[4] D. Harting, J. C. Kluyver, A. Kusumegi, R. Rigopoulos, A. M. Sachs, G. Tibell, G. Vanderhaeghe, and G. Weber, Phys. Rev. Letters 3, 52 (1959).
[5] A. M. L. Messiah, Phys. Rev. 86, 430 (1952).
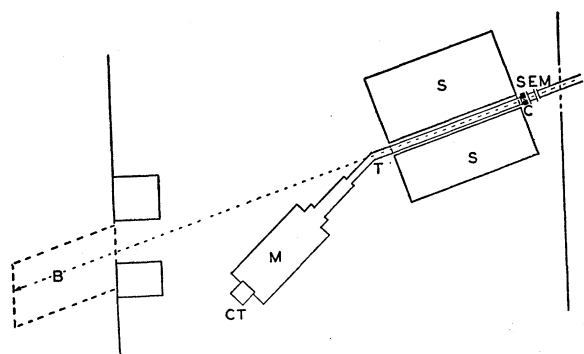[6] J. M. Luttinger, Phys. Rev. 86, 571 (1952).

FIG. 1. Plan view of the experimental area. Secondary emission monitor *SEM*, collimator *C*, shielding *S*, target *T*, spectrometer magnet *M*, counter telescope *CT* and beam catcher *B*.

The first attempt to measure this ratio was made with 340-Mev protons.[2] Recent measurements have been made at 600 Mev[4] at *CERN* and at 450 Mev in this laboratory.[3] At *CERN* the ratio has been measured to about 5% accuracy at one angle and measurements at other angles are being made. In this laboratory the ratio was measured to about 12% over a range of 20° in the center-of-mass system. The present experiment consists of a measurement at one angle to 7% accuracy.

METHOD

The cross sections were obtained by detecting only the heavy particles. To reduce background the particles were analyzed by a high-resolution magnetic spectrometer[7] and then detected by a counter telescope which employed both range and pulse-height descrimination.
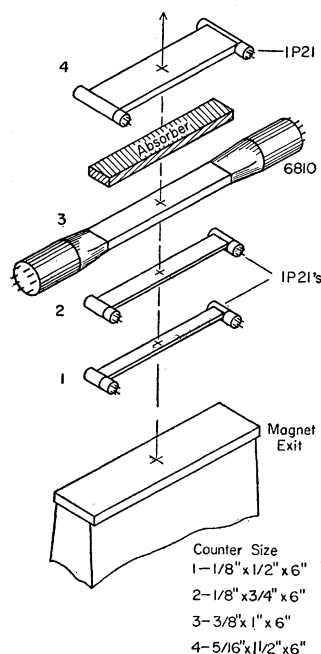

FIG. 2. Counter telescope.

Counter Size
1—1/8"x1/2"x6"
2—1/8"x3/4"x6"
3—3/8'x 1"x6"
4—5/16"x1 1/2"x6"

[7] A. V. Crewe, Rev. Sci. Instr. 29, 880 (1958).

The experimental area is shown in plan view in Fig. 1. The extracted protons from the Chicago synchrocyclotron[8] pass through a secondary emission monitor (*SEM*) and a collimator (*C*) and are focused on a CD_2 target or a matched carbon target (*T*). Except in the neighborhood of the secondary emission monitor, the protons travel in vacuum to the targets in order to reduce background radiation. A concrete shield *S* covers the region of the beam monitor and collimator and lead shielding encloses the counter telescope (*CT*). After passing through the target, the protons enter a shielded beam catcher (*B*).

The H^3 and He^3 travel in vacuum through the magnet to the quadruple counter telescope shown in Fig. 2. The first three counters are connected in coincidence and the fourth in anticoincidence. An absorber was placed between counters 3 and 4 to stop the H^3, while allowing lighter particles of the same momentum to enter counter
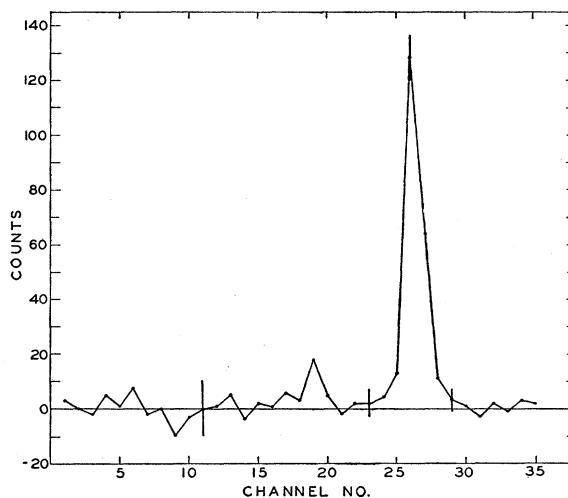

FIG. 3. Pulse-height spectrum showing CD_2-C counts for H^3 production. The large peak represents H^3, the small peak H^2. Only representative statistical errors are shown.

4. This was not sufficient discrimination, however, to allow the straight-forward counting of H^3 particles. The number of counts at any given momentum was orders of magnitude greater than the number of triton counts due to the inefficiency of the anticoincidence counter and the general background, thus masking the counts of interest. Therefore pulse-height analysis of the pulses in counter 3 was also used. This enabled us to separate the real effect from the background. For the detection of He^3, counter 2 was removed from the telescope because the range of these particles is only a few mm of scintillator. Both He^3 and deuterons of the same p/Z will then stop in counter 3. Protons of the same p/Z will enter counter 4 and be discriminated against. Pulse-height analysis of the pulses from counter 3 separated the He^3 from the deuterons. The triton counting rate

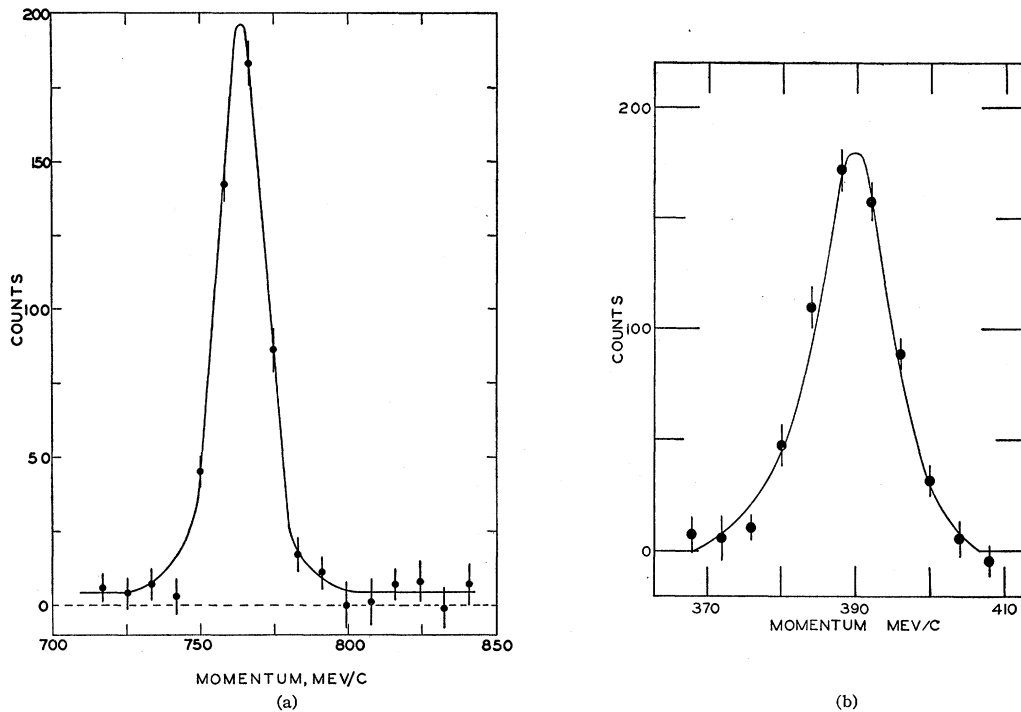[8] A. V. Crewe and U. E. Kruse, Rev. Sci. Instr. 27, 5 (1956).

FIG. 4. (a) Curve showing H^3 counts versus momentum. The width of the defining counter corresponds to 9.2 Mev/c. (b) Curve showing He^3 counts versus momentum. In this momentum range the width of the defining counter corresponds to 4.2 Mev/c.

was remeasured with counter 2 removed to insure that counter 2 was 100% efficient.

Each scintillator was viewed at both ends by photo-tubes whose output signals were balanced and added. The signal from counter 3 was split. One half was used for the coincidence circuit and one half was fed to a 50-channel pulse-height analyzer through a fast gate,[9] which is opened by a $12\overline{34}$ coincidence.

After the usual electronic checks were made, the pulse-height spectra for carbon and CD_2 targets were recorded at several values of magnet current through the range appropriate to the p/Z of the H^3 (or He^3). A plot at a suitable magnet current of CD_2-C counts versus the channel number shows a peak in the channels corresponding to the H^3, as shown in Fig. 3. These counts were then summed over a sufficient number of channels to insure that all the heavy particles were included, and a plot was made of counts versus momentum as shown in Figs. 4(a) and 4(b) for H^3 and He^3, respectively.

There is an appreciable background for the tritons. In order to allow for this, measurements were made at a number of magnet currents off the momentum peak for both H^3 and He^3 as shown, and a base line was established for calculating the area of the peak.

The resolution of the magnet and the momentum spread of the H^3 and He^3 are such that the width of the exit focal spot is greater than that of the defining counter

[9] E. L. Garwin, Rev. Sci. Instr. **30**, 373 (1959).

($\frac{1}{2}$-in.). The total flux of H^3 or He^3 through the magnet is obtained by dividing the area of the curves in Fig. 4 by the momentum range accepted by the defining counter. To find the proportionality factor between the width of the defining counter and the momentum range accepted we replaced the $\frac{1}{2}$-in., defining counter by two
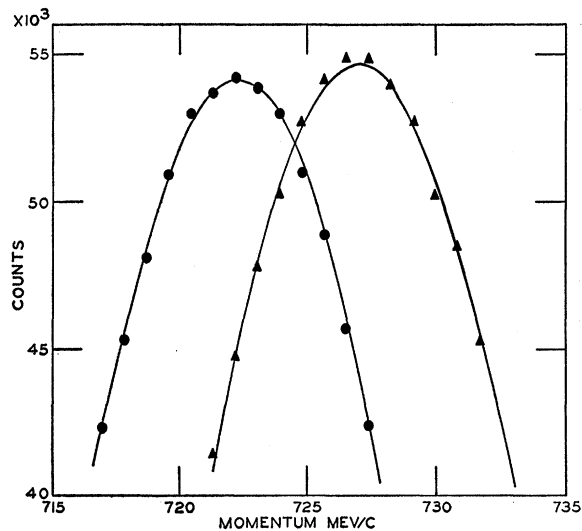

FIG. 5. Curves show the tops of peak from p-p elastic scattering. The two curves are obtained by substituting for the usual $\frac{1}{2}$-in. wide defining counter two $\frac{1}{4}$-in. wide counters side by side. The distance between the centers gives the momentum width of the counter at this momentum.
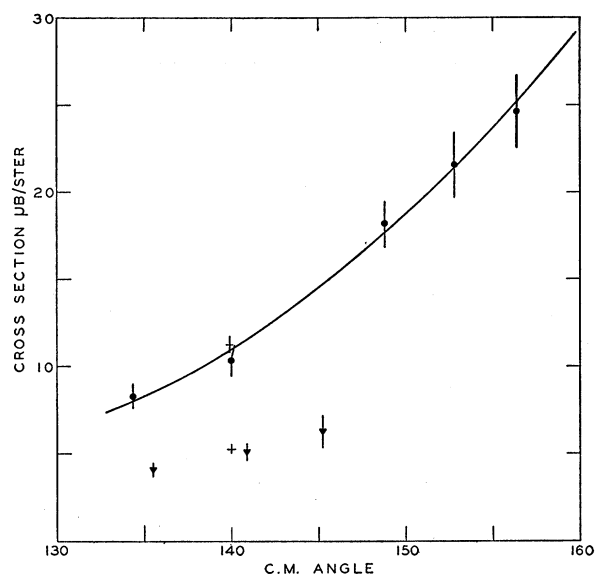
FIG. 6. Cross section versus c.m. angle. Filled circles and triangles refer to cross sections for the previous run for H^3 and He^3, respectively. The crosses show the two measurements from this run. The curve is a least squares fit of a parabola to the previous H^3 data.

$\frac{1}{4}$-in. counters, $1A$ and $1B$, side by side and studied p-p elastic scattering from a CH_2 target using a suitable range of magnet currents. By plotting $1A34$ and $1B34$ coincidences versus momentum we obtained two curves, as shown in Fig. 5, displaced from one another on the momentum axis. This displacement together with an accurate measurement of the center-center separation of the $\frac{1}{4}$-in. counters and of the width of counter 1 gave us the momentum range accepted by this counter. Measurements of this were made at the two p-p scattering angles which gave protons of the same p/Z as the H^3 and He^3.

The H^3 and He^3 results were normalized to give absolute cross sections by comparing p-p elastic scattering counting rates, using 134 coincidences, with published[10] p-p cross sections. An analysis of the CD_2 target showed an impurity of 2.2% H_2, which was corrected for in these cross sections.

The cross sections obtained in this way are listed in Table I together with the results from a final analysis of the data of the previous run.[3] This analysis allowed us to calculate the absolute cross sections from the data and had the effect of reducing the relative magnitudes of He^3 data which were published previously.

[10] W. N. Hess, Revs. Modern Phys. 30, 368 (1958).

The ratios from the previous run quoted in Table I were obtained by comparing the He^3 data with a parabola fitted to the H^3 data (see Fig. 6).

The errors on the ratios include statistical errors and 2% inaccuracy in the measurement of the momentum widths of counter 1. For the absolute cross sections we also included a 3% error for the measured and published p-p cross sections.

Combining the results at 140° c.m. for the two runs we arrive at a final ratio of 2.17±0.13.

## THEORETICAL CORRECTIONS AND CONCLUSIONS

The theoretical ratio for these cross sections is two, but there are two corrections to apply: (1) the difference in the center-of-mass kinetic energies available in the two cases and (2) a Coulomb effect.

The effect of the latter has not been calculated.

TABLE I. Summary of data.

θ^0 lab	θ^0 c.m.	Particle	Run	$(d\sigma/d\Omega)_{c.m.}$, μb	$(d\sigma/d\Omega)_{H^3}$: $(d\sigma/d\Omega)_{He^3}$
11	145.2	He^3	1	6.44±0.94	2.34±0.37
12	140.9	He^3	1	5.23±0.52	2.26±0.26
12	140.0	He^3	2	5.41±0.29	2.13±0.15
13	135.5	He^3	1	4.19±0.38	2.08±0.22
8	156.4	H^3	1	25.3 ±2.2	
9	152.8	H^3	1	22.1 ±2.0	
10	148.8	H^3	1	18.6 ±1.4	
12	140.0	H^3	1	10.6 ±0.91	
12	139.9	H^3	2	11.55±0.49	
13	134.4	H^3	1	8.47±0.74	

An estimate has been made in the case of the former correction, using a theory due to Ruderman[11] and Bludman,[12] who relate the cross sections for $p+p \rightarrow \pi^+ + d$ and $p+d \rightarrow \pi^+ + H^3$. We assumed for this calculation that $\Psi_{H^3} = \Psi_{He^3}$ and that the cross section for the reaction

$$p+p \rightarrow \pi^+ + d,$$
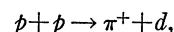
is not energy dependent at our energies. This calcualtion indicates that the ratio will be increased and the effect is less than 6%.

We conclude that the hypothesis of charge independence is valid for these reactions within the accuracy of our experiment.

[11] M. Ruderman, Phys. Rev. 87, 383 (1952).
[12] S. A. Bludman, Phys. Rev. 94, 1722 (1954).