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Measurement of the Rotation Parameter R in Proton-Proton Scattering at 140 Mev*

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The proton-proton rotation parameter R has been measured at a laboratory energy of 140.5 Mev over a range of scattering angles θ_2 by means of a triple-scattering experiment. The following values were obtained: $\theta_2(\text{lab})=15°$, -0.252 ± 0.030; 20°, -0.227 ± 0.028; 25°, -0.271 ± 0.035; 30°, -0.146 ± 0.037; 35°, -0.151 ± 0.055; 40°, -0.047 ± 0.080.

INTRODUCTION

THIS experiment continues the program of measuring $p-p$ scattering parameters at 140 Mev. The cross section and polarization[1] and the depolarization parameter D[2] have already been measured. The R parameter, introduced by Wolfenstein,[3] measures the rotation of the polarization of a transversely polarized proton beam.

The experiment can most readily be described by reference to Fig. 1. A proton beam having its polarization vertical passes through a solenoid magnet (P). The polarization precesses 90° about the direction of motion, so that on leaving the solenoid the beam has a polarization P_1 in the horizontal plane and perpendicular to the direction of motion. The beam strikes a liquid hydrogen target (2), and particles scattered through an angle θ_2 in the horizontal plane, defined by counters A, B, then strike the analyzing scatterer (3). Particles scattered through an angle θ_3 in the vertical plane containing the line from the hydrogen target to the analyzing scatterer are detected by the counter telescopes CD or EF. The angle θ_3 of these telescopes can be reversed in sign; we denote by U and D, respectively, the up and down positions. The direction of the current through the solenoid, and hence the sign of the incident polarization P_1, can be reversed; we denote the two possibilities by N (for normal) and R (for reversed).

Let $I(k,m)$ be the rate of fourfold coincidences ($ABCD$ or $ABEF$) for counter telescope position k and solenoid current direction m, where k is either U or D, and m is either N or R. We then define

$$e_{3s}=\frac{I(D,N)+I(U,R)-I(U,N)-I(D,R)}{I(D,N)+I(U,R)+I(U,N)+I(D,R)}. \qquad (1)$$

The product of incident polarization and analyzing power, P_1P_3, is measured following the same convention as to solenoid current direction and telescope position. (The current leads to the solenoid were so connected as to give a positive P_1P_3.) Then R is defined[3] by the equation

$$e_{3s}=P_1P_3R. \qquad (2)$$

The solenoid magnet was not essential to the experiment. In its absence, the measurement would be performed by having the hydrogen scattering in a vertical plane, and the analyzing scattering in a plane tilted with respect to both vertical and horizontal. The apparatus would be rotated through 90° about the incident beam. The use of a solenoid makes the design and operation of the scattering table much simpler. It further eliminates many types of systematic errors, as discussed later.

The present Article describes the experiment in less detail than Thorndike.[4]

EXPERIMENTAL PROCEDURE

The Beam

The beam used for this experiment was the polarized proton beam of the Harvard synchrocyclotron.[5] It passes through the solenoid magnet (P), and is defined by the slits (G), $1\frac{1}{2}$ in. wide by 2 in. high. The beam energy is $144\frac{1}{2}$ Mev and the polarization is 65%. With the solenoid off, there is a linear energy variation across the width of the beam of 5 ± 2 Mev/in., the south side having the higher energy.

While the beam passes through the solenoid, its polarization precesses about the magnetic field,[6] through an angle roughly proportional to $1/\sqrt{E}$. The solenoid field was kept within 1% of the value which rotates the polarization of a 147-Mev beam through 90°, and a $144\frac{1}{2}$ Mev beam through $90\frac{3}{4}$°.

In addition to the desired effect of rotating the polarization of the beam, the solenoid has the undesired effect of changing the direction and intensity distribution of the beam, with a resulting change in the zero position of the analyzing scattering angle θ_3. As calculated in reference 4 the transverse momentum given to a proton

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[1] J. N. Palmieri, A. M. Cormack, N. F. Ramsey, and Richard Wilson, Ann. Phys. **5**, 229 (1958).

[2] C. F. Hwang, T. R. Ophel, E. H. Thorndike, and Richard Wilson, Phys. Rev. **119**, 352 (1960).

[3] L. Wolfenstein, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, 1956), Vol. 6, p. 43.

[4] E. H. Thorndike, Ph.D. thesis, Harvard University, 1960 (unpublished).

[5] Calame *et al.*, Nuclear Instr. **1**, 169 (1956).

[6] H. Mendlowitz and K. M. Case, Phys. Rev. **97**, 33 (1955).

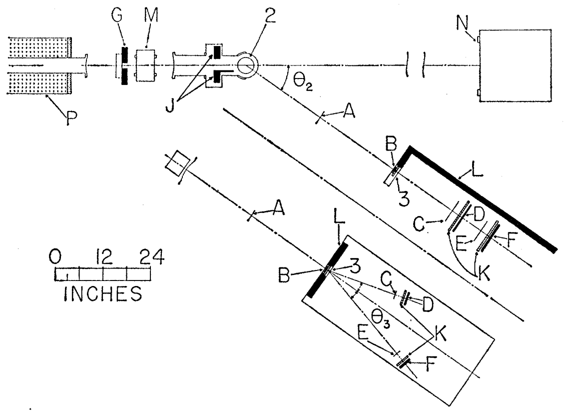

FIG. 1. Scale drawing of the experimental arrangement for R(140 Mev) showing: (2) hydrogen target, (3) analyzing scatterer, (A–F) scintillation counters, (G) main defining slits, (J) antiscattering slits, (K) copper absorbers, (L) iron shielding, (M) ion chamber, (N) Faraday cup, and (P) solenoid magnet.

by the fringing field at the entrance to the solenoid has its direction rotated within the solenoid such that the point of arrival of the proton at the end of the solenoid has been rotated by 16.1° about the solenoid axis, as compared to its point of arrival with the field off. This rotation is in the same sense as that of the polarization, and the two will be reversed together. That this rotation will cause a change in the intensity distribution of the beam defined by the main slits can be seen by reference to Fig. 2. If the solenoid is off, the edge of the beam is vertical, and outside the region defined by the slits. If the solenoid is on, the edge cuts either the upper or lower corner of the region defined by the slits, and hence reduces the beam intensity in that region. If the main slits are moved too far from the beam edge in an attempt to reduce this effect, the average beam energy and polarization are reduced.

If the mean direction of the beam through the solenoid is not parallel to the axis, but rather has a component normal to it and in a horizontal plane, this component will be bent up for one solenoid current direction and down for the other, causing the beam to rise or fall.

The momentum transferred to the beam by the entrance and exit fringing fields will not in general cancel, and the residual momentum may be in the vertical direction.

The Target Chamber

The liquid hydrogen target (2), 4 in. in diameter by $5\frac{1}{2}$ in. high, was made of 0.002 in. thick beryllium copper. That portion of the circumference through which the incident beam did not pass was surrounded by an aluminum heat shield, 0.003 in. thick. For that portion of the circumference through which the incident beam did pass, the heat shield was 0.00025 in. thick.

The exit window of the target vacuum chamber was made from 0.007 in. thick Mylar, which wrinkled when the target chamber was evacuated such that its effective thickness was increased by 25%. The intersection of this exit window with the beam could be "seen" by the AB telescope, and hence contributed background counts.

Adjustable antiscattering slits (J) prevented particles scattered from the main slits and ion chamber from striking counters A or B, and prevented particles scattered from the entrance window to the target vacuum chamber from striking counter B, though some may have struck A. The slit on the side to which the scattered beam was to be observed was positioned, experimentally, to give minimum background without reducing the intensity of the incident beam appreciably. The slit on the opposite side was moved away from the beam as far as possible, to minimize the number of particles scattered off it into the counters.

The Scattering Table

The superstructure of the scattering table (not shown in Fig.1) was two aluminum channels, parallel to the twice scattered beam (the line $2,A,B$). One channel defined a horizontal plane 24 in. below the twice scattered beam; the other, a vertical plane 24 in. away from the twice scattered beam and on the side away from the direct (once scattered) beam. This superstructure mounted on a base which pivoted in a ball and socket beneath the hydrogen target. The assembly could be set at a desired angle from a nominal zero angle by means of a bar, and could be levelled by screw adjustments.

The counters A–F were attached, directly or indirectly, to the two aluminum channels.

Telescopes CD and EF were each attached to arms which pivoted about an axis mounted on the vertical channel and perpendicular to it.

The telescopes could be both moved away from the vertical channel and levelled. A transit mounted at the end of the horizontal channel away from the θ_2 pivot was adjusted to sweep in the vertical plane containing the twice scattered beam. Using this transit, the telescopes were moved away from the vertical channel until the centers of their scintillators lay in this plane.

The dimensions of the counters A–F are given in Table I. Counter B was defining counter for all particles

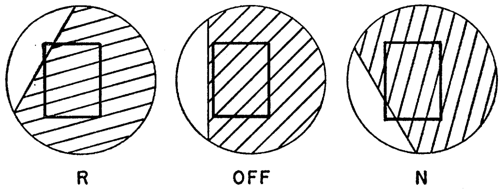

FIG. 2. Sketch showing intersection of beam with defining slits, for three solenoid current conditions: reversed, off, normal. The angle of rotation of the beam has been exaggerated.

TABLE I. Dimensions of the scintillation counters.

Counter	Height (in.)	Width (in.)	Thickness (in.)
A	3	$3\frac{3}{4}$	$\frac{3}{32}$
B	2	2	$\frac{3}{32}$
C,E	2	6	$\frac{1}{8}$
D,F	$3\frac{3}{8}$	8	$\frac{5}{16}$

scattered from the hydrogen target. Counter *A* served to insure that the particles did in fact come from the general area of the target. Counters *C*, *E* were the defining counters for all particles scattered from the analyzing scatterer. Counters *D* and *F* were present so that discrimination against low energy particles could be obtained by placing copper absorbers (*K*) between *C* and *D* and between *E* and *F*. A range curve was taken with θ_3 equal to zero, and the absorber used for the e_{3s} measurement chosen to be less than the value at the knee of the range curve by an amount slightly more than the loss in range due to scattering at the value of θ_3 used for the e_{3s} measurement, namely 15°.

Counters *C*, *D*, *E*, and *F* were shielded from air-scattered protons from the direct beam by shielding (*L*) shown in Fig. 1. The analyzing scatterer, placed immediately after counter *B*, had a cross sectional area large compared to *B*. The scatterer was carbon, $\frac{1}{2}$ in. thick for θ_2 from 15° to 30°, $\frac{3}{8}$ in. thick for $\theta_2=35°$, and $\frac{1}{4}$ in. thick for $\theta_2=40°$.

Figure 1 shows the scattering table as it was used for θ_2 scatterings to the south. For scatterings to the north, the scattering table was "reflected" about the vertical plane containing the twice scattered beam.

Electronic Circuitry

Counters *A*–*F* were made from Pilot *B* plastic scintillators, connected by short light pipes to 6810A phototubes. The outputs of these counters were fed into a multichannel coincidence circuit, whose operation is described in reference 4.

Coincidences selected and counted were *AB*, *CD*, *EF*, *ABCD*, *ABEF*, *BCD*, *BEF*. Random coincidences were studied by delaying the appropriate signals by twice the period of the cyclotron rf. The only significant random background was *AB* in random coincidence with *CD* or *EF*. Its magnitude is listed in Table II.

TABLE II. Magnitude of background and random coincidence subtractions relative to corrected counting rate.

		Random coincidences		Background	
θ_2		*ABCD*	*ABEF*	*ABCD*	*ABEF*
15°	North	0.5%	0.6%	9.0%	9.5%
	S	0.6	0.9	9.4	8.7
20°	N	0.4	0.9	4.0	4.0
	S	0.6	1.3	3.3	3.3
25°	N	0.4	0.8	1.8	1.6
	S	0.7	1.5	2.4	2.9
30°	N	0.4	2.0	2.7	2.8
	S	0.8	4.0	2.1	2.2
35°	N	0.6	2.1	3.0	2.5
	S	0.8	3.7	2.2	2.2
40°	N	0.8	3.0	2.2	2.8
	S	1.1	6.0	2.1	2.2

An ionization chamber (*M*) and a Faraday cup (*N*) were used as beam monitors. The ratio of the two monitors depended on the solenoid current direction, varying as much as 2% from normal to reversed. This causes no error in *R* because solenoid directions are averaged over. If one sums over solenoid directions, the short term differences (within a given e_{3s} measurement) averaged 0.2%. The long term differences (from e_{3s} measurement to background measurement) averaged $2\frac{1}{2}$%.

Alignment

The critical alignment is that for the zero position of θ_3. All other alignments produce negligible errors by comparison, as detailed in reference 4. The θ_3 zero changed when the solenoid was reversed. Rather than try to align separately for solenoid normal and solenoid reversed, it was decided to align with the solenoid off, measure the shift in alignment caused by the solenoid, and correct for it. This was done at every θ_2 angle.

The alignment was changed by the electromagnetic effects described earlier; in addition, polarization effects at the hydrogen scattering coupled with the finite size of the beam at the hydrogen target and of counter *B* would cause changes in beam direction and intensity distribution at the analyzing scatterer, and hence in the θ_3 alignment, when the solenoid was reversed. For the "normal" solenoid current direction, particles scattered at the hydrogen target would prefer to scatter down; for the "reversed" direction, they would prefer to scatter up. This shift in zero position on reversing the solenoid is proportional to $P_1P_2(\theta_2)/\sin\theta_2$; at $\theta_2=15°$ it was calculated to be 0.1°.

In an attempt to reduce the change in alignment, the vertical opening of the main slits was reduced, the horizontal positioning of the main slits was varied, and the path of the beam through the solenoid was varied both by rotating the solenoid in a horizontal plane and by moving the quadrapole focusing magnets in a horizontal plane. A systematic and detailed study was not made. As the main slits were moved from south to north, the change in alignment decreased at an average rate of 0.16° per inch, in qualitative agreement with the effect illustrated in Fig. 2. A reduction of the vertical slit opening from 2 in. to $1\frac{1}{2}$ in. decreased the change in alignment from 0.17° to 0.14°; for some effects it should decrease the change in the ratio $1:(\frac{3}{4})^2$, for others, there should be no decrease. Varying the path of the beam through the solenoid caused small inconsistent changes, suggesting that the electromagnetic deflections tended to cancel each other.

These and other alignment effects could be qualitatively explained, and the change in alignment was of the same order as predicted. Time prevented detailed quantitative checks.

As shown in reference 4, the error in e_{3s} from misalignment is very nearly equal to the first moment, M, of the twice scattered beam times the fractional change in counting rate between $\theta_3=14°$ and $\theta_3=16°$, $(1/\sigma)\times(d\sigma/d\theta)$, for analyzing scattering at $\theta_3=15°$. A measurement of misalignment must thus approximate M.

The misalignments were measured by sweeping the *CD* and *EF* telescopes through small θ_3 in one degree steps, detecting the twice scattered beam by quadruple coincidences. A pair of such beam profiles for the *EF* telescope, with the solenoid normal and reversed, is shown in Fig. 3. Note the shift in profile position with solenoid direction.

The profiles were analyzed in two ways. The first moment $\int A(\theta_3)\theta_3 d\theta_3$ was approximated by

$$\Delta\theta_0=\sum_{-n}^{n} A(\theta_{3i})\theta_{3i}, \tag{3}$$

summing in one-degree steps. [$A(\theta_3)$ is the quadruple coincidence rate at the angle θ_3.] For the *CD* telescope, $n=8°$; for the *EF* telescope, $n=7°$. The magnitude of the sum was less than that of the integral, but by not more than 6% for *CD*, and not more than 3% for *EF*.

A misalignment by the "slope method" was calculated by the expression:

$$\Delta\theta_s(\theta_i)=\frac{2[A(\theta_i,D)-A(\theta_i,U)]}{A(\theta_{i-1},D)+A(\theta_{i-1},U)-A(\theta_{i+1},D)-A(\theta_{i+1},U)}. \tag{4}$$

It was found that $\Delta\theta_0$ could be approximated by an average of $\Delta\theta_s$ over $\theta_i=4°$ and 5° for *CD*, and over 3° and 4° for *EF*. The former was low by $(2\frac{1}{2}\pm3)\%$; the latter was high by $(11\pm5)\%$.

Since the "slope method" required only half as many alignment points to be taken, it was used for most measurements. The misalignments inferred from it differed systematically from the first moments by not more than 10%, and the two telescopes differed in opposite directions, such that their weighted average was in error by not more than 4%. The systematic error of 10% of the alignment correction term listed in Table VI includes this error plus those from the approximation of the alignment correction term by $(M)(1/\sigma)(d\sigma/d\theta)$.

In addition to the systematic errors mentioned above, three random errors in θ_3 alignment were included; one from counting statistics, one from reproducibility ($\frac{2}{3}$ of the deviation from the mean), and a 10% error to include dead time, monitoring, movements of the beam, and other small effects. In most cases this general error was dominant.

Miscellaneous Procedures

Background from protons scattered by nuclei other than hydrogen was measured by evacuating the hydrogen target and increasing the copper absorbers in the *CD* and *EF* telescopes to compensate for the change in energy due to the absence of hydrogen. The background measurement at $\theta_2=15°$ immediately followed the e_{3s} measurement at $\theta_2=15°$, since at that angle the background was largest.

The P_1P_3 measurement differed from that for a D measurement[2,7] only in the ways which the e_{3s} measurement differed from the e_{3n} measurement for D.[2,7] The energy shim was, on some occasions, checked for all three solenoid conditions. The θ_3 alignment was made with solenoid off, and misalignment with solenoid on was measured. The P_1P_3 asymmetry was measured by alternately reversing solenoid current and counter configuration. Since the θ_3 misalignment need not be measured as accurately for the P_1P_3 measurement as for the e_{3s} measurement, a more abbreviated alignment profile was frequently taken, and the misalignment inferred from an equation similar to that for $\Delta\theta_s$. Usually, a two-angle profile was taken before the P_1P_3 measurement and a one angle check at its conclusion.

For the measurements at $\theta_2=$north 20° and 35°, the coincidence circuit was malfunctioning, and *BCD* and *BEF* triples were used in place of quadruple coincidences, with a slight resultant increase in background. The counting statistics for the runs at south angles were appreciably better than those for the runs at north angles.

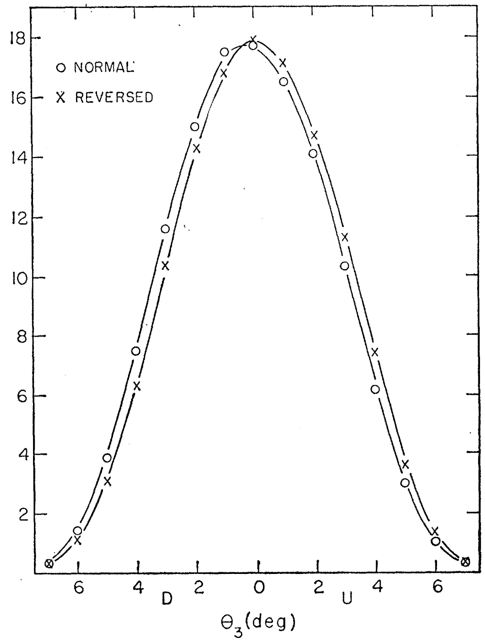

FIG. 3. Profiles of the twice-scattered beam taken with the EF telescope, for solenoid normal and reversed, at $\theta_2=25°$ north.

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[7] E. H. Thorndike and T. R. Ophel. Phys. Rev. 119 362 (1960).

TABLE III. Random errors in *R* from various sources.

θ_2	e_{3s}		P_1P_3		$(1/\sigma)(d\sigma/d\theta)$		
	Stat	Align	Stat	Align	Stat	Monitor	Total
15° North	0.036	0.009	0.008	0.001	0.007	0.002	0.038
South	0.029	0.017	0.008	0.002	0.013	0.002	0.037
20° N	0.038	0.006	0.010	0.002	0.008	0.002	0.040
S	0.030	0.007	0.008	0.002	0.009	0.002	0.034
25° N	0.050	0.030	0.017	0.003	0.019	0.003	0.064
S	0.031	0.008	0.009	0.002	0.013	0.003	0.036
30° N	0.058	0.012	0.011	0.002	0.012	0.003	0.061
S	0.038	0.010	0.008	0.001	0.010	0.003	0.043
35° N	0.106	0.012	0.005	0.000	0.017	0.005	0.108
S	0.051	0.016	0.017	0.003	0.015	0.005	0.059
40° N	0.218	0.022	0.075	0.004	0.049	0.008	0.237
S	0.074	0.006	0.002	0.000	0.023	0.008	0.079

ANALYSIS AND RESULTS

Scattering Energy and Angle

The mean energy of the hydrogen scattering was determined to be 140.5±1.0 Mev from the range curves taken in copper at each θ_2. As for the *D* measurements,[2,7] all energy measurements are based on the polyethylene range curves of Rich and Madey[8] and the copper range curves of Aron, Hoffman, and Williams,[9] with ranges lowered by 1% to give agreement with the polyethylene curve, based on a comparison at 140 Mev. The stated error does not include the uncertainty of these range-energy relations, but rather indicates the deviation of the various measurements from the mean. The energy scale is thus consistent with those for other measurements in this laboratory.[1,2] Use of Sternheimer's new relation[10] would lower the energy 1% if his CH_2 curve is used, and not at all if the Cu curve is used. The energy varied with the solenoid by not more than $\frac{1}{2}$ Mev. Normal averaged higher than reversed by $\frac{1}{4}$ Mev.

The energy resolution was determined by the energy lost by the beam in traversing the target (8 Mev) and the linear energy variation across the beam at the main slit ($7\frac{1}{2}$ Mev). The rms deviation of the scattering energy was calculated from these figures to be ±3 Mev.

A knowledge of the beam polarization was not needed for this experiment, and hence no measurements of beam polarization were performed. An extrapolation of the measurements of others to the slit positions used here suggests a polarization of 0.65±0.04.

The angular resolution of the hydrogen scattering varied from ±1.6° rms at $\theta_2=15°$, to ±2.0° rms at $\theta_2=40°$.

The angular resolution of the analyzing scattering is relevant only to higher order alignment corrections. It was measured to be ±3.4° rms for *ABCD*, and ±2.6° rms for *ABEF*.

Combination of Measurements

The e_{3s} measurements for *ABCD* and *ABEF* were combined, weighting by the square of the reciprocal of the (combined statistical and alignment) error. The P_1P_3 measurements for both counters were combined, weighting both equally so that monitoring errors would cancel. Errors in *R* from e_{3s} counting statistics, e_{3s} alignment, P_1P_3 statistics, P_1P_3 alignment, $(1/\sigma)(d\sigma/d\theta)$ statistics, and monitoring, were calculated, and are listed in Table III. The measurements for θ_2 north and θ_2 south were combined, weighting by the square of the reciprocal of $P_1P_3\Delta R$, where ΔR is obtained by combining the errors mentioned in the preceding sentence. (If ΔR alone were used, the results would be biased towards higher values of P_1P_3.)

Corrections

The magnitude of the correction for θ_3 misalignment can be inferred from the systematic error of 10% of the correction listed in Table VI. It was always in such direction as to make *R* more negative.

Since the energy of second and third scatterings was different during background and hydrogen runs, a small correction to the measured background was needed.[2,7] The correction is shown in Table IV. There is an additional uncertainty in this correction as compared to that of references 2,7 arising from the lack of knowledge of the values of *R* for elastic scattering, as compared with the knowledge of *D* and P_2.

TABLE IV. Corrections to *R* from variation in energy across defining slits, and from energy difference between background and hydrogen measurements.

θ_2	δR(slit energy)	δR(background energy)
15°	−0.009	−0.009
20°	−0.009	−0.001
25°	−0.010	0
30°	−0.010	0
35°	−0.015	0
40°	−0.011	0

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[8] M. Rich and R. Madey, University of California Radiation Laboratory Report UCRL-2301, 1954 (unpublished).

[9] W. A. Aron, B. G. Hoffman, and F. C. Williams, Atomic Energy Commission Report, AECU-663, 1949 (unpublished).

[10] R. Sternheimer, Phys. Rev. **115**, 137 (1959).

TABLE V. Errors in R systematic from north θ_2 to south θ_2.

θ_2	ΔR(shim)	ΔR(background energy)
15°	0.006	0.003
20°	0.005	0.002
25°	0.007	0.002
30°	0.005	0.002
35°	0.004	0.004
40°	0.002	0.004

As in references 2,7, a correction to R for the variation in energy across the main defining slits is required. It was assumed that with the solenoid off there was a 5 ± 2 Mev/inch variation in energy across the slits horizontally, that the solenoid rotated this variation 16° out of the horizontal, and that the beam had diverged, preserving its energy variation, to 3 in. high at the hydrogen target. The correction was made using the values of $(1/\sigma)(d\sigma/d\theta)$ from Table VII, and an energy dependence of analyzing scattering cross section from data of Gerstein[11] and Dickson and Salter.[12] In addition to the 40% error from uncertainty of the energy variation with solenoid off, a 30% error has been included for additional uncertainty of the energy variation at the hydrogen target with the solenoid on. The telescope absorbers were chosen as in reference 7 so that no error arises from a combination of excessive absorber and this energy change.

Errors

The e_{3s} measurement may be thought of as an up-down asymmetry averaged, with appropriate choice of signs, over both solenoid directions, or as a normal-reversed asymmetry averaged over both counter positions. To the extent that a spurious asymmetry from one reversal is not in any way coupled to an asymmetry from the other reversal, the spurious asymmetry cancels in the averaging process and introduces no error in e_{3s}.

The error introduced by any mechanical up-down asymmetry, such as nonuniformity of the scintillation counters, cancels on averaging over solenoid directions. It seemed desirable to show that any up-down asymmetries were small even though they canceled upon averaging. Thus up-down asymmetries were measured with the solenoid off for hydrogen scattering at $\theta_2=$ north 25° ($+0.013\pm0.010$), and for the P_1P_3 configuration shimmed for 25° with the analyzing scatterer in place (-0.008 ± 0.008), and with the analyzing scatterer removed (-0.011 ± 0.027).

The monitoring efficiency, the scattering angle θ_2, and the average beam energy, change on solenoid reversal; resulting errors cancel in measuring the up-down asymmetry.

The most important possible source of error that is systematic as θ_2 is varied is an alignment of the angle θ_3 which changes with solenoid direction. It is believed that the alignment procedure is adequate; a 10% error in the alignment correction is included in Table VI. Also systematic as θ_2 is varied is the correction for energy variation across the main slit. Errors which are systematic from θ_2 north to θ_2 south but independent as the magnitude of θ_2 is changed include that from incorrect energy shimming for P_1P_3 (and consequent incorrect value) for which ±1 Mev was allowed, and the correction to the background for the energy difference. These are listed in Table V.

Results

The final values of R with their "total errors," a quadratic combination of all random and systematic

TABLE VI. Final values of R(140 Mev).

			Systematic errors			
θ_2	R	ΔR random	ΔR 10% align	ΔR slit	ΔR total	Weighting factor
15° North	−0.235		0.007			0.479
South	−0.268		0.015			0.521
combined	−0.252	0.027	0.011	0.005	0.030	
20° N	−0.202		0.007			0.393
S	−0.242		0.009			0.607
comb	−0.227	0.027	0.008	0.004	0.028	
25° N	−0.390		0.016			0.261
S	−0.229		0.012			0.739
comb	−0.271	0.032	0.013	0.005	0.035	
30° N	−0.161		0.009			0.343
S	−0.139		0.008			0.657
comb	−0.146	0.035	0.009	0.005	0.037	
35° N	−0.044		0.009			0.302
S	−0.198		0.014			0.698
comb	−0.151	0.053	0.012	0.007	0.055	
40° N	−0.249		0.019			0.197
S	+0.003		0.011			0.803
comb	−0.047	0.079	0.012	0.006	0.080	

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[11] G. Gerstein, J. Niederer, and K. Strauch, Phys. Rev. **108**, 427 (1957). See also G. L. Gerstein, private communication to C. F. Hwang.

[12] J. M. Dickson and D. C. Salter, Nuovo cimento **6**, 235 (1957). See also measurements of J. M. Dickson, B. Rose, and D. C. Salter, reported by A. E. Taylor, *Reports on Progress in Physics* (The Physical Society, London, 1957), Vol. 20, p. 125.

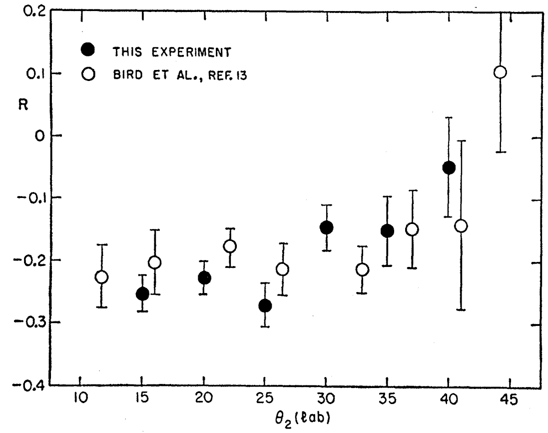

FIG. 4. R(140 Mev) for proton-proton scattering vs laboratory scattering angle θ_2. Shown also are the measurements of Bird, *et al.*[13] at 142 Mev.

errors, are plotted against lab scattering angle in Fig. 4 and listed in Table VI. Shown also are the measurements of Bird *et al.*[13] at 142 Mev.

Quantities characterizing the analyzing scattering, namely P_1P_3, $(1/\sigma)(d\sigma/d\theta)$, and the mean energy of analyzing scattering E_3, are listed in Table VII. P_3 is plotted vs E_3 in Fig. 5 (P_1 was taken as 0.65). Shown also in this figure are the P_3 values from D(98 Mev)[7] and from D(142 Mev),[2] and the polarization measurements of Dickson and Salter.[12] $(1/\sigma)(d\sigma/d\theta)$ is plotted vs E_3 in Fig. 6. Shown also are values for D(98 Mev)[7] and D(142 Mev),[2] and from measurements of Gerstein[11] and of Dickson and Salter.[12]

Two measurements of R have not been included in these results. A measurement at θ_2 = south 25° gave a value of -0.272 ± 0.036 for R (error random only). Had it been included with the other two measurements, the final value of R would have become more negative by 0.0003, or 1% of the stated total error. The *ABEF* counts did not seem internally consistent during this measurement. For one solenoid direction and counter position, the counts of the four sets averaged 806, but included one set of 710.

TABLE VII. Quantities characterizing the analyzing scattering.

θ_2		P_1P_3	$(1/\sigma)(d\sigma/d\theta)$	E_3
15°	North	0.265±0.010	0.151±0.016	117.1
	South	0.262±0.009	0.178±0.016	117.4
	combined	0.264±0.007	0.165±0.011	117.3
20°	N	0.237±0.012	0.130±0.015	108.3
	S	0.225±0.008	0.158±0.015	108.5
	comb	0.230±0.007	0.147±0.011	108.4
25°	N	0.165±0.008	0.137±0.017	97.7
	S	0.172±0.007	0.127±0.014	97.9
	comb	0.170±0.006	0.129±0.011	97.8
30°	N	0.126±0.009	0.104±0.013	85.5
	S	0.131±0.008	0.109±0.013	86.6
	comb	0.129±0.006	0.107±0.010	86.2
35°	N	0.072±0.012	0.076±0.014	73.9
	S	0.087±0.008	0.125±0.013	73.4
	comb	0.083±0.007	0.110±0.010	73.6
40°	N	0.038±0.012	0.057±0.015	61.7
	S	0.056±0.009	0.071±0.015	60.1
	comb	0.053±0.007	0.068±0.012	60.4

A measurement at θ_2 = north 40° gave a value of $+0.061\pm0.230$ for R. Had it been included with the other two measurements, the final value of R would have become more positive by 0.018, or 22% of the stated total error. This measurement was made when the A counter was not functioning; the background was 50% higher than for the other north 40° measurement. The antiscattering slit was very close to the unscattered beam, and may have been contributing low-energy counts. The e_{3s} measurements for the two counters differed by 2.4 standard deviations. The $(1/\sigma)(d\sigma/d\theta)$ measurements differed by 3.5 standard deviations; that for the *EF* telescope (0.186 ± 0.027) seemed high compared to other values as shown in Fig. 6.

Although no major error in experimental procedure or functioning of apparatus during the two measurements was discovered, it was decided to exclude them from the final results, since they seemed not internally consistent, and since their exclusion caused only small changes in the final results.

Consistency

The measurements of e_{3s}, P_1P_3, and $(1/\sigma)(d\sigma/d\theta)$ from the *CD* telescope were compared with those from the *EF* telescope. For e_{3s}, three out of twelve measurements differed by more than one standard deviation; for P_1P_3, four out of twelve measurements so differed; for $(1/\sigma)(d\sigma/d\theta)$ seven out of twelve measurements so differed. All measurements differed by less than two standard deviations.

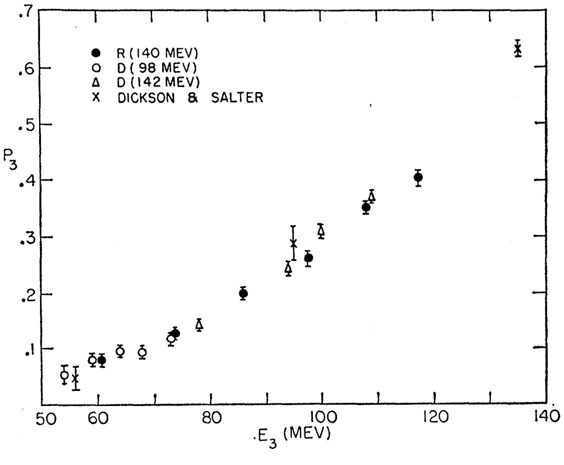

FIG. 5. Analyzing power P_3 vs mean energy of analyzing scattering E_3, from the experiments measuring R(140 Mev), D(98 Mev),[7] and D(142 Mev).[2] Polarization measurements of Dickson and Salter[12] are also shown. The analyzing scattering angle θ_3 is 15°.

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[13] L. Bird, D. N. Edwards, B. Rose, A. E. Taylor, and E. Wood, Phys. Rev. Letters 4, 302 (1960).

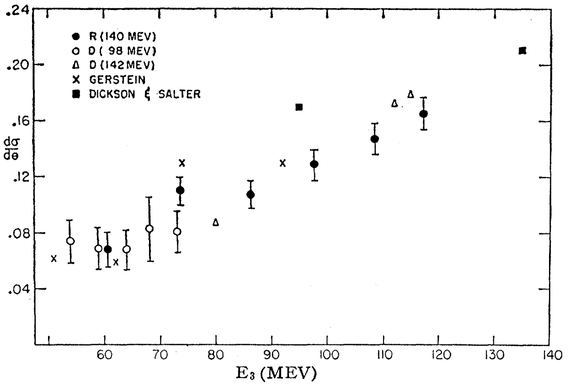

FIG. 6. $(1/\sigma)(d\sigma/d\theta)$ vs the mean energy of analyzing scattering E_3, from the experiments measuring R(140 Mev), D(98 Mev),[7] and D(142 Mev).[2] Measurements of Gerstein[11] and of Dickson and Salter[12] are also shown. The analyzing scattering angle θ_3 is 15°.

The measurement of R, P_1P_3, and $(1/\sigma)(d\sigma/d\theta)$ from θ_2 north were compared with those from θ_2 south. For R, three out of six measurements differed by more than one standard deviation; the measurements at $\theta_2=25°$ differed by 2.2 standard deviations. For P_1P_3, two out of six measurements differed by more than one standard deviation; none differed by more than two standard deviations. For $(1/\sigma)(d\sigma/d\theta)$ three out of six measurements differed by more than one standard deviation; at $\theta_2=35°$, the measurements differed by 2.6 standard deviations.

The four partial asymmetries were compared for both e_{3s} measurements and P_1P_3 measurements. For P_1P_3 there were neither up-down nor normal-reversed asymmetries that were statistically significant. The differences $P_1P_{3N}-P_1P_{3R}$ and $P_1P_{3U}-P_1P_{3D}$ differed from zero by more than two standard deviations on one occasion out of 48 comparisons. (The subscripts N, R, U, D indicate the parameter not varied.)

For e_{3s}, the value of e_N-e_R for north θ_2 suggest an admixture of A (see reference 4); if one assumes the value of A predicted by Gammel and Thaler,[14] then the longitudinal component of polarization P_{X0} equals 0.13. For south θ_2, there is no evidence for a nonzero value of P_{X0}. (This can be explained in terms of the main slit defining a different portion of the beam.) The values of e_U-e_D for south θ_2 suggest a monitoring variation, normal to reversed, of 1.6%. There is no evidence for such a variation at north θ_2, again explicable in terms of slit positioning. The asymmetry differences e_N-e_R and e_U-e_D are nonetheless greater than zero by more than two standard deviations on only three out of 48 occasions.

In summary, all variations are quite compatible with statistical expectations or explicable in terms of a definite (nonerror producing) effect such as longitudinal polarization.

DISCUSSION

The values of R reported here are in agreement with those of Bird *et al.*,[13] as can be seen from Fig. 4.

The values of P_3 from R(140 Mev), D(98 Mev),[7] and D(142 Mev)[2] agree well with each other, and quite satisfactorily with the measurements of Dickson and Salter,[12] considering the finite angular resolution and poor discrimination against inelastic scattering of the first three measurements.

Values of $(1/\sigma)(d\sigma/d\theta)$ vary smoothly with energy in reasonable agreement with the values of others.[2,7,11,12] The $\theta_2=35°$ measurement, at $E_3=74$ Mev, seems perhaps two standard deviations above the smooth curve suggested by the other points. It was at this angle that the north and south measurements agreed poorly (see section "Consistency"). If the value of $(1/\sigma)(d\sigma/d\theta)$ suggested by the smooth curve had been used for the misalignment correction, R at 35° would have been more positive by 0.025, or 45% of the total error.

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[14] J. L. Gammel and R. M. Thaler, Phys. Rev. **108**, 163 (1957).