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Proton-Proton Depolarization at 98 Mev*

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The triple scattering depolarization parameter D for proton-proton scattering has been measured at 98 Mev, as follows: 10° (lab), 0.00±0.08; 15°, 0.00±0.07; 20°, 0.00±0.08; 25°, −0.12±0.10; 30°, −0.11 ±0.16.

INTRODUCTION

We report a measurement of the proton-proton depolarization parameter D at 98 Mev by a triple scattering experiment. Previous measurements have been made at 140 Mev,[1,2] at 315 Mev,[3] and at 635 Mev.[4]

The apparatus and experimental techniques used in this measurement, except where described differently, are the same as those used in the 140-Mev D measurement of Hwang *et al.*,[1] reported in the preceding paper. The experimental arrangement for the large angle measurements ($\theta_2=20°$, 25°, and 30°) differs from Fig. 1 of the preceding paper only by the addition of the beam energy degrader; that for the small angle measurements ($\theta_2=10°$ and 15°) is shown in Fig. 1 of this article. The components of these figures are referred to in the text by either numbers or letters in parenthesis.

EXPERIMENTAL DETAILS

The Beam

The beam used for this experiment was the polarized proton beam of the Harvard synchrocyclotron.[5] A 1-in. wide by 3-in. high portion of the beam was defined by slits (G, preceding paper) and was lowered in energy from 147 Mev to 103 Mev by a polyethylene block (H), 6.7 g/cm² thick.[6] The multiple scattering caused by this energy degrader had a rms projected angle of $1\frac{1}{2}°$, half-width. The divergence of the beam before degrading was small compared to $1\frac{1}{2}°$. The mean energy of the beam at the center of the full hydrogen target was 98±1 Mev. The energy spread, full width at half maximum, was 7 Mev. The polarization was 0.67±0.02. There was a linear energy variation across the width of the beam of 5±2 Mev; the S side having the higher energy. A small correction to D is required because of this energy variation.

The Target Chamber

The liquid hydrogen target (2), 4 in. in diameter by $4\frac{5}{8}$ in. high, was made of 0.003-in. thick Mylar. 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. For the small angle measurements, a 1-in. by 3-in. opening was cut in the heat shield, allowing approximately 60% of the beam to pass through.

The exit window of the target vacuum chamber was, in the case of the large angle measurements, 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 the beam with this exit window could be "seen" by the AB telescope, and hence contributed background counts. In the case of the small-angle measurements, this intersection could not be "seen" by the AB telescope, and hence did not contribute to the background.

Adjustable antiscattering slits (J) prevented particles scattered by the energy degrader from striking counters A or B, and prevented particles scattered by the entrance window to the target vacuum chamber from striking counter B. 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. For the small angle measurements, the extending wing on this slit was removed, as shown in Fig. 1, to enable the slit to be moved farther from the beam.

The Scattering Table

The dimensions of the counters A–F are given in Table I. The scintillators were Pilot B plastic connected by short light pipes to 6810 A phototubes. Counter B

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[6] All energy measurements are based on the polyethylene range curves of M. Rich and R. Madey, University of California Radiation Laboratory Report UCRL-2301, 1954 (unpublished), and the copper range curves of W. A. Aron, B. G. Hoffman, and F. C. Williams, Atomic Energy Commission Report AECU-663, 1949 (unpublished), with ranges lowered by 1% to give agreement with the polyethylene curve, based on a comparison at 140 Mev.

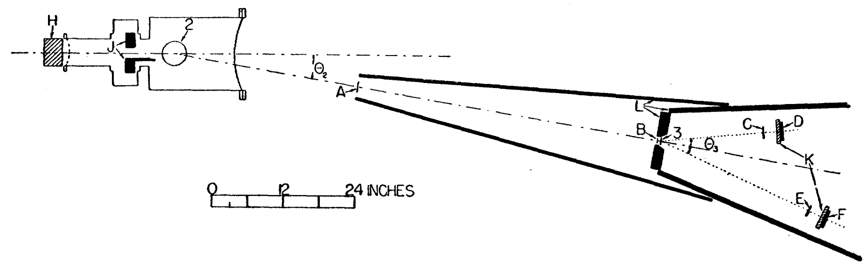

FIG. 1. Scale drawing of the experimental arrangement for small angle (10° and 15°) measurements, showing: (2) hydrogen target, (3) analyzing scatterer, (A–F) scintillation counters, (H) polyethylene beam degrader, (J) antiscattering slits, (K) copper absorbers, and (L) iron shielding.

was the defining counter for all particles scattered from the hydrogen target. Counter A served to ensure that the particle 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, 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_{3n} 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_{3n} measurement, namely 15°. The shielding (L) reduced the number of air-scattered protons that struck the counters. The analyzing scatterer (3) was a piece of carbon, larger in cross-sectional area than counter B, and having a thickness of $\frac{1}{2}$ in. for $\theta_2=10°$ and 15°, $\frac{3}{8}$ in. for 20°, $\frac{1}{4}$ in. for 25°, and $\frac{1}{8}$ in. for 30°. Counter B also acted as an analyzing scatterer.

Alignment of Apparatus

The only critical alignment was that of ensuring that $\theta_{3N}=\theta_{3S}$. Both telescopes CD and EF were set, to high accuracy, at equal angles N and S of a nominal zero angle, by means of a fixed bar. The zero angle was determined by requiring that the counting rate $ABCD$ be equal at $\theta_3=3\frac{1}{2}°$ N and $3\frac{1}{2}°$ S, and that the counting rate $ABEF$ be equal at $\theta_3=2\frac{1}{2}°$ N and $2\frac{1}{2}°$ S. At these angles, the counters detected particles not scattered by the analyzing scatterer; the inside edge of the defining counter (C or E) was about $\frac{1}{4}$ in. away from the zero line. A profile taken by sweeping θ_3 through small angles had shown the doubly scattered beam to be symmetric about its zero position.[1] It was thus felt that by the above method, the difference $\theta_{3N}-\theta_{3S}$ could be measured to an accuracy better than 0.05°.

At each value of θ_2, N and S, before an e_{3n} measurement, both sets of counters were aligned so that $|\theta_{3N}-\theta_{3S}|$ was less than 0.1°; after the e_{3n} measurement, alignment was checked. The e_{3n} values were corrected for measured θ_3 misalignments, using an experimentally determined change in counting rate with angle. These corrections rarely exceeded half the error of e_{3n} due to counting statistics.

The change in doubly scattered proton energy with θ_2, and hence across counter B, would produce a misalignment if the copper telescope absorber was too thick.[8] This misalignment would be odd in θ_2 and thus affect P_2', but not D. At each angle the alignment was checked with sufficient extra absorber added to the telescope to assure that this effect would cause no trouble.

Since the θ_3 alignment was done operationally, using the counters, rather than by optical sighting, the position of the θ_2 pivot and of the hydrogen target was not particularly critical. These and other alignments, such as the levelness of the beam and the heights of the counters, could readily be made to such accuracy that they introduced negligible error into the results.

Monitoring

The beam was monitored with a Faraday cup (N, preceding paper). Because the two sets of counters ($ABCD$ and $ABEF$) required θ_3 scatterings of opposite senses, a monitoring error would tend to cancel out. The values of e_{3n} for $ABCD$ and $ABEF$ would be in error by equal amounts, but in opposite senses. For the purpose of optimizing the beam intensity, an ion chamber (M, preceding paper) was used.

Backgrounds

Background from random coincidence events was investigated by delaying the signal from various of the counters by an amount large compared to the resolving time of the coincidence circuit. The only events with counting rates high enough to be important were A in random coincidence with BCD or BEF, and AB in random coincidence with CD or EF. In the former case, since BCD exceeded $ABCD$ by only from 3% to 14%, and similarly for BEF and $ABEF$, the measured random rate was reduced to these percentages of itself before being used to correct the data. This type of random event was important only at $\theta_2=10°$, where it amounted to 0.9% of the total counting rate. At 15°,

TABLE I. Dimensions of the scintillation counters.

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

TABLE II. Depolarization and polarization for p-p scattering at 98 Mev, and analyzing power and energy of analyzing scattering. The p-p polarization values of Palmieri *et al.*[a] at 95 Mev are listed for comparison.

θ_2 (lab)	D	P_2'	P_2	P_2 (Palmieri)	P_3	E_3 (Mev)
10°	0.00±0.08	0.06±0.05	...	0.092±0.010	0.119±0.010	73
15°	0.00±0.07	0.11±0.05	...	0.130±0.007	0.094±0.010	68
20°	0.00±0.08	0.02±0.06	0.116±0.008	0.120±0.007	0.097±0.009	64
25°	−0.12±0.10	0.12±0.07	0.095±0.008	0.112±0.007	0.081±0.010	59
30°	−0.11±0.16	0.00±0.10	0.093±0.008	0.095±0.007	0.054±0.013	54

[a] See reference 8.

it was 0.2% of the total, and at larger angles it was expected to be still smaller. Since the CD and EF rates, due largely to neutron background, were from 10 to 30 times larger than the quadruples rate, there was no need to reduce the measured random rate of the latter-mentioned case. It amounted to 1% to 2% of the total counting rate.

Background from protons scattered by nuclei other than protons 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 magnitude of the measured background was 12% of the total counting rate at 10°, 5% at 15° and 20°, $2\frac{1}{2}$% at 25°, and $1\frac{1}{2}$% at 30°. Since the energy conditions at the second and third scatterings with target empty were not the same as with the target full, the measured background required a small correction.

P_1P_3 Measurement

For the measurement of P_1P_3, the hydrogen target was evacuated, and θ_2 was set at zero degrees. The energy of the beam was lowered, by lead absorbers and copper shims placed just after the polyethylene block (H), to within $\frac{1}{2}$ Mev of the energy it would have upon leaving the full hydrogen target after scattering through the angle θ_2 for which e_{3n} had been measured. The beam intensity was reduced until the AB rate could be conveniently scaled. With the scattering table at zero degrees, and with the beam intensity reduced, the Faraday cup could no longer be used as a beam monitor. The AB rate was used instead. Scaler dead time losses made this form of monitoring less reliable than the Faraday cup; consequently the asymmetries measured from $ABCD$ and $ABEF$ were weighted equally to give the final value (see section on Monitoring).

The energy of the beam striking the third scatterer was the same as for the e_{3n} measurement; the polarization of the beam was P_1. Hence the asymmetry obtained by reversing the sense of θ_3, as for the e_{3n} measurement, was P_1P_3. As in the e_{3n} measurement, the counters were aligned before each P_1P_3 measurement, the alignment checked after the measurement, and the value of P_1P_3 corrected for the measured misalignment.

Scattering from material other than the carbon analyzing scatterer is not background, in that it was present during both e_{3n} and P_1P_3 measurements. Random background events were not important. Since CD and EF counts were due to protons scattered at the analyzing scatterer, rather than neutrons as in the e_{3n} case, they had roughly the same asymmetry as the fourfold coincidences, and consequently, so would the random events.

RESULTS

The values of D obtained in this experiment are plotted against center-of-mass scattering angle in Fig. 2. The theoretical prediction of Gammel and Thaler[7] at 100 Mev is also shown. The values of D, plus those of P_2', P_2, P_3, and the energies of the analyzing scattering E_3, are listed in Table II. The values of P_2 obtained by Palmieri *et al.*[8] at 95 Mev are listed for comparison.

The values of P_3 were obtained by weighting the results for $ABCD$ and $ABEF$ equally. All other values were obtained by weighting the two sets of data by the square of the reciprocal of their errors. Agreement between the two sets of e_{3n} measurements was generally satisfactory, though at $\theta_2=15°$ N, they differed by three standard deviations.

The change in antiscattering slit configuration between $\theta_2=10°$, 15° N and 10°, 15° S resulted in a change in the efficiency of the monitoring. Consequently, values of P_2 could not be obtained at these

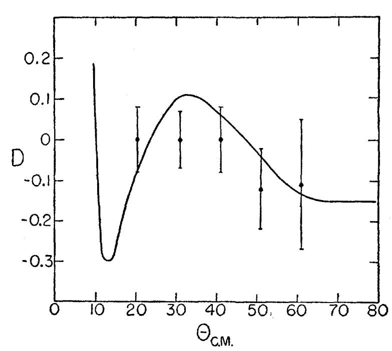

FIG. 2. D for p-p scattering at 98 Mev vs center-of-mass scattering angle. The curve shows the values predicted at 100 Mev by Gammel and Thaler (reference 8).

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angles. In the formulas (7, 8 of the preceding paper) for D and P_2', Palmieri's values of P_2 were used for these angles while those of this experiment were used at 20°, 25°, and 30°. The uncertainty in D and P_2' arising from the choice of P_2 is negligible compared to the error from counting statistics.

The angular resolution of the second scattering is 3° rms full width at $\theta_2=10°$ and 15°, and 4° at $\theta_2=20°$ 25°, and 30°. The multiple scattering in the energy degrader contributed the bulk of this, namely 3°.

The errors quoted include errors in e_{3n} and P_1P_3 due to counting statistics and misalignment. The only significant error is counting statistics of the e_{3n} measurement. The largest correction to D for misalignment is 0.04, at $\theta_2=30°$. The largest change in D from adjustment of background for correct energy conditions (see section on Backgrounds) is 0.02, at $\theta_2=10°$. The correction to D from the energy variation across the incident beam (see section on The Beam) is between 8% and 14% of the quoted error.

The values of D reported here lie below those measured at 140 Mev[1] by an amount consistent with the Gammel and Thaler potential,[7] which potential correctly predicts values of D at 140 Mev and 315 Mev.[3]

The values of P_2' agree with the P_2 measurements of Palmieri *et al.*,[8] as they should if *p-p* scattering is invariant under time reversal. The values of P_2 also agree, within statistics, with the measurements of Palmieri *et al.*[8]

The values of P_3, when plotted as a function of scattering energy, fall on the smooth curve suggested by the polarization measurements of Dickson and Salter[9] and of Hwang *et al.*[1]

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Decay of μ^- Mesons Bound in the K Shell of Light Nuclei

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For μ^- mesons bound in the K shell of light nuclei of atomic number Z, we calculate the decay electron spectrum accurately up to the first power in Z, both for point and extended nuclei. The decay rate is evaluated accurately up to the second power for point nuclei. Our results for the spectrum show the Doppler smearing of its upper end as obtained previously, and demonstrate the small effect of the nuclear extension. The decay rate is obtained as a monotonically decreasing function of Z, and we cannot explain recent experiments which show a maximum of the decay rate around $Z\sim26$. We also find that the decay rate in second order decreases much more slowly with Z than what would be obtained from a phase space consideration alone.

I. INTRODUCTION

It has been known for a considerable time that the decay characteristics of a μ^- meson should be different from those of a μ^+ meson. This is due to the fact that μ^- mesons brought to rest in matter end up in a bound state of a mesonic atom, believed to be the ground state,[1] and decay from there. Decay electron spectra have been obtained theoretically,[2–5] essentially for the case of muons bound by light point nuclei only, and show predominantly a Doppler smearing of the upper end of a free muon decay spectrum caused by the orbital motion of the muon ("Primakoff effect"). Recent experiments,[6–11] however, have until now measured only the decay rate λ_- of bound μ^- mesons. Their results show significant deviations from the free μ^+ decay rate λ_+, such that $\lambda_->\lambda_+$ for $Z\sim26$, $\lambda_-<\lambda_+$ for $Z\gtrsim30$. A simple phase space argument[8] gives λ_-/λ_+ as a monotonically decreasing function of Z (the

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