Polarization in Proton-Proton Scattering at 130, 170, and 210 Mev*

E. BASKIR,† E. M. HAFNER, A. ROBERTS, AND J. H. TINLOT
University of Rochester, Rochester, New York
(Received January 21, 1957)

Using a 90% polarized proton beam, we have measured the polarization in p–p scattering at center-of-mass angles between 20 and 81 degrees at 130 Mev, between 31 and 82 degrees at 170 Mev, and between 14 and 112 degrees at 210 Mev. The first two of these measurements are consistent with data previously published; the third involves an energy in the neighborhood of which earlier detailed work has not been done. The measurements are fitted by functions of the form

$$P(\theta)\sigma(\theta)=\sin\theta\cos\theta\sum_{n=0}^{K}b_{2n}\cos^{2n}\theta,\quad\text{where}\quad K=0,\ 1,\ \text{or}\ 2.$$

At 210 Mev, a three-parameter least-squares fit yields $b_0=(2.78\pm0.16)$ mb/sterad, $b_2=(-2.24\pm0.17)$ mb/sterad, and $b_4=(2.96\pm0.77)$ mb/sterad. Statistical analysis of the data at 210 Mev indicates that F-wave effects, and in particular a nonvanishing b_4, are required for description of the scattering.

INTRODUCTION

FOLLOWING the measurement[1] in this laboratory of the polarization in proton-proton scattering at 210 Mev and 45 degrees in the center-of-mass system, it seemed desirable to extend the work to other energies and angles, utilizing the highly polarized external scattered beam of our synchrocyclotron. The angular dependence of the polarization at a given energy would reveal the relative contributions of triplet states with $J>0$, and would, together with measurements of the absolute value of the polarization, provide new data with which p-p interaction theory could be compared. Measurements at energies both higher and lower than that of the original measurement have recently been carried out by other workers.[2–7] The present report summarizes the results of our measurements at 130, 170, and 210 Mev in the center-of-mass angular interval between 20 and 90 degrees. It serves to interpolate and to overlap the existing data.

The experiment was done in a conventional way. An external polarized beam was produced by elastic scattering of protons from an internal target. The magnitude of the polarization of this beam was calibrated by measuring the asymmetry in a second identical scattering; the known incident polarization could then be used to convert asymmetries observed in scattering from hydrogen to corresponding values of the p-p polarization. These procedures make use of familiar theorems[8] connecting asymmetry with polarization.

APPARATUS

The polarized beam was produced by bombarding a carbon or a beryllium target with protons circulating at the full energy of the 130-inch cyclotron. Protons scattered into a small solid angle centered at 15 degrees emerged from the cyclotron vacuum tank through a 10-mil aluminum window. The beam was focused by a wedge magnet through an ion-chamber monitor and onto a second target of polyethylene or of liquid hydrogen. A flux of 10^6 to 10^7 protons per minute was available at the second target. Protons second-scattered into the forward direction were counted by a range telescope. A 69-mil copper diffusing screen, introducing 0.023 rms radian of multiple Coulomb scattering, was mounted at the exit face of the wedge magnet in order to produce uniformity of illumination of the second target.

The first set of runs was made by taking CH_2-C differences, using polyethylene and graphite second scatterers of equal stopping power. The scatterers were mounted with planes normal to the axis of the detecting telescope. The final set of runs employed a second scatterer consisting of a styrafoam-insulated cylinder filled with liquid hydrogen and providing a hydrogen thickness of 0.59 g/cm^2.

The scatterers and detecting telescope were mounted on an accurate rotatable assembly originally constructed for measurements[9] of polarization in n-p scattering. The assembly can be remotely rotated about a vertical axis through the target center and positioned to within two minutes of arc; the counter telescope axis is then known to a precision of this order.

Conventional coincidence circuits and pulse generators, with resolving times of 25 to 50 millimicroseconds and dead times of 0.1 to 0.2 microsecond, were employed with the range telescope. The accidental rates were less

* Research supported by the U. S. Atomic Energy Commission. This work constitutes a part of Dr. Baskir's Ph.D. thesis.
† National Science Foundation pre-doctoral fellow; now at Shell Development Company, 3737 Bellaire Boulevard, Houston, Texas.
[1] Oxley, Cartwright, and Rouvina, Phys. Rev. **93**, 806 (1954).
[2] J. M. Dickson and D. C. Salter, Nature **173**, 946 (1954).
[3] A. E. Taylor, *Sixth Annual Rochester Conference on High Energy Physics* (Interscience Publishers, Inc., New York, 1956).
[4] D. Fischer and J. Baldwin, Phys. Rev. **100**, 1445 (1955).
[5] Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **93**, 1430 (1954).
[6] Marshall, Marshall, and de Carvalho, Phys. Rev. **93**, 1431 (1954).
[7] Kane, Stallwood, Sutton, Fields, and Fox, Phys. Rev. **95**, 1694 (1954).
[8] L. Wolfenstein and J. Ashkin, Phys. Rev. **85**, 947 (1952).
[9] Roberts, Tinlot, and Hafner, Phys. Rev. **95**, 1099 (1954).

than 3% of the coincidence rates at the smallest scattering angle, and rapidly became negligible as the angle was increased. Dead-time losses were not significant.

PROCEDURE

At the beginning of each set of runs, a surveyor's transit was adjusted to provide a line of sight roughly coinciding with the path of the strongest flux leaving the wedge magnet. Mu-metal magnetic shields were located along this path in order to insure that proton trajectories did not deviate from straight lines by more than 0.0002 radian. The range-telescope axis and its axis of rotation were then brought into accurate coincidence with the optical line, and collimators and spray shields were set with accurate symmetry about the same line. The target was then centered on the axis of rotation, but its position was not critical since the collimating system determined the scattering volume. Angles of scattering to left and right of the polarized beam were measured with respect to the optical line of sight. The precision of the angular readings was of the order of two minutes of arc, but their accuracy was dependent upon the symmetry of illumination of the scattering volume and could not easily be estimated. A check against angular error was therefore advisable, and in this experiment it was made during preliminary runs by observing that the asymmetry in backward scattering (the angle chosen was about 113 degrees in the center-of-mass system) exhibited the proper sign reversal about 90 degrees.

TABLE I. Polarization in proton-proton scattering. E_1 = beam energy (Mev); T_1 = first target; P_1 = beam polarization; θ_2 = second scattering angle (center-of-mass system); T_2 = second target (H_2 or CH_2).

E_1	T_1	P_1	T_2	θ_2	$e_H(\theta_2)$	$P_H(\theta)$
210	C	0.90	H_2	13°42′	0.195±0.07	0.217±0.08
	C	0.90	H_2	21°04′	0.225±0.019	0.250±0.021
	Be	0.865	CH_2	21°04′	0.247±0.09	0.286±0.10
	C	0.90	H_2	31°32′	0.280±0.009	0.311±0.010
	C	0.90	CH_2	31°32′	0.293±0.024	0.326±0.027
	Be	0.865	CH_2	31°32′	0.279±0.024	0.323±0.027
	C	0.90	H_2	42°00′	0.289±0.009	0.321±0.010
	Be	0.865	CH_2	42°00′	0.292±0.024	0.338±0.028
	C	0.90	H_2	47°12′	0.272±0.006	0.302±0.007
	Be	0.865	CH_2	47°12′	0.320±0.019	0.370±0.021
	C	0.90	H_2	52°22′	0.260±0.010	0.289±0.011
	C	0.90	CH_2	52°22′	0.321±0.048	0.357±0.053
	Be	0.865	CH_2	52°22′	0.290±0.020	0.335±0.022
	C	0.90	CH_2	57°31′	0.343±0.042	0.381±0.047
	C	0.90	H_2	62°40′	0.241±0.016	0.268±0.018
	Be	0.865	CH_2	62°40′	0.238±0.023	0.275±0.027
	C	0.90	H_2	67°48′	0.197±0.009	0.219±0.010
	C	0.90	CH_2	71°00′	0.200±0.033	0.222±0.037
	Be	0.865	CH_2	72°53′	0.154±0.018	0.178±0.020
	C	0.90	H_2	83°02′	0.069±0.011	0.077±0.012
	Be	0.865	CH_2	92°58′	−0.005±0.023	−0.006±0.027
	Be	0.865	CH_2	112°36′	−0.151±0.028	−0.175±0.032
170	C	0.90	H_2	31°16′	0.214±0.016	0.238±0.018
				41°38′	0.226±0.008	0.251±0.009
				41°38′	0.231±0.009	0.257±0.010
				46°48′	0.226±0.011	0.251±0.012
				51°57′	0.206±0.012	0.229±0.013
				62°11′	0.180±0.025	0.200±0.028
				67°16′	0.142±0.015	0.158±0.017
				82°28′	0.076±0.019	0.084±0.021
130	C	0.90	H_2	20°38′	0.134±0.03	0.149±0.03
				46°24′	0.160±0.011	0.178±0.012
				66°46′	0.090±0.014	0.100±0.015
				81°54′	0.026±0.017	0.029±0.019

Photomultiplier voltages and amplifier gains were set with the telescope reading a direct beam of 200-Mev protons. The settings were checked periodically during runs by observing the sensitivity of counting rates to fifty-volt changes in the photomultiplier supplies. The true coincidence rates seldom changed by a significant amount. Care was also taken during runs to maintain cyclotron operating conditions and focusing magnet current so as to maximize the proton flux in the energy interval 200–220 Mev. Background corrections were significant in this experiment and, for the case of the liquid hydrogen scatterer, were based on counting rates from an empty duplicate container. Polarization data at reduced energies were obtained by inserting 7.9 or 14.6 g/cm² of polyethylene into the beam immediately ahead of the final collimator. We observed that the absorbers introduced small losses in intensity and small increases in background, and we assumed[10] that they introduced negligible depolarization effects.

EXPERIMENTAL RESULTS

Beam Polarization

The polarization of the external beam produced in the scattering of 225-Mev protons from carbon at the laboratory angle 15.0±0.2 degrees was found by meas-

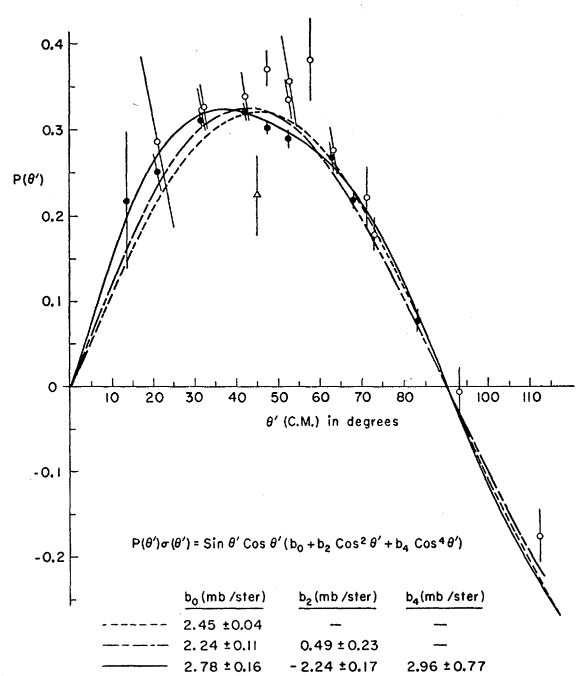

FIG. 1. Angular dependence of the p-p polarization at 210±4 Mev. The solid circles are data from a liquid hydrogen scatterer; the open circles are data from CH_2-C differences; the triangle is the measurement by Oxley *et al.* (reference 1). The curves represent one-, two-, and three-parameter fits to these data, as indicated. θ' in this and subsequent figures has the same meaning as θ in the text.

[10] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949); E. Heiberg *et al.*, Phys. Rev. **97**, 250 (1955).

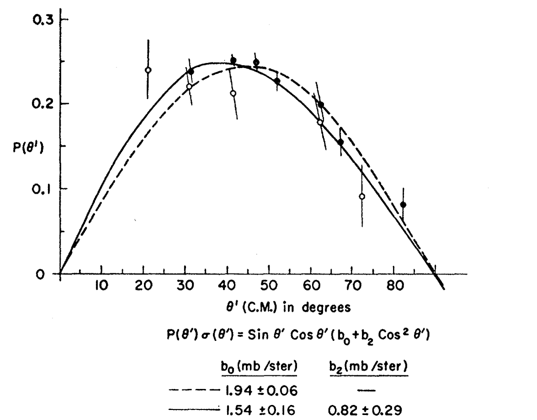

FIG. 2. Polarization at 170±5 Mev. The solid circles are data from this experiment; the open circles are the measurements by Fischer and Baldwin (reference 4). The curves are least-squares fits, with parameters as indicated.

uring the asymmetry produced in second scattering from carbon at the same angle. The value adopted for the beam polarization effective during hydrogen runs was 0.90±0.03, where the quoted standard deviation is five times the error arising from counting statistics alone. The largest contributions to the total error came from an uncertainty in correcting for the 14-Mev energy difference between first and second carbon scatterings, the 0.2-degree uncertainty in first angle, uncertainties in correcting for finite solid angles, and an estimate of the error involved in correcting for the fact that the beam polarization was calibrated at a detector energy threshold 15 Mev above the one used during the p-p measurements. Our result is in good agreement with the independent value 0.89±0.02 obtained for 14-degree scattering in an experiment already reported.[11] Measurements on a beam produced by a beryllium first target under identical conditions

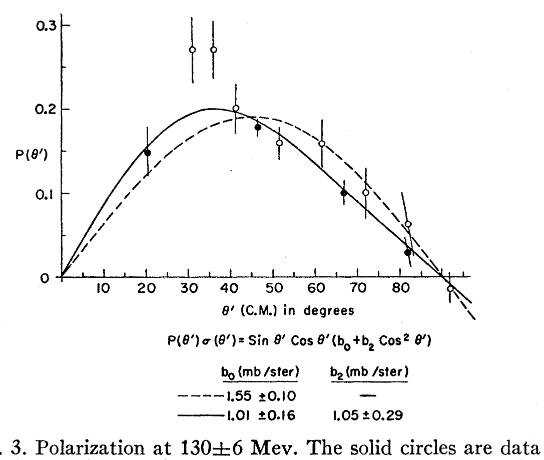

FIG. 3. Polarization at 130±6 Mev. The solid circles are data from this experiment; the open circles are the measurements by Dickson and Salter (reference 2). The curves are least-squares fits, with parameters as indicated.

[11] Chesnut, Hafner, and Roberts, Phys. Rev. **104**, 449 (1956).

gave the ratio of polarization from beryllium to that from carbon as 0.961±0.013 at 225 Mev, and the beryllium polarization as 0.865±0.03.

Proton-Proton Polarization

At center-of-mass angles above 21 degrees, the asymmetry in scattering by hydrogen of the 210-Mev polarized proton beam was measured by the yield of protons from polyethylene and graphite scatterers of equal stopping power. Appropriate corrections were made for the different carbon densities of these scatterers and for the background counting rates. At angles below about 31 degrees, the CH_2-C subtraction method became very difficult because of the fact that the carbon count became many times as large as the hydrogen

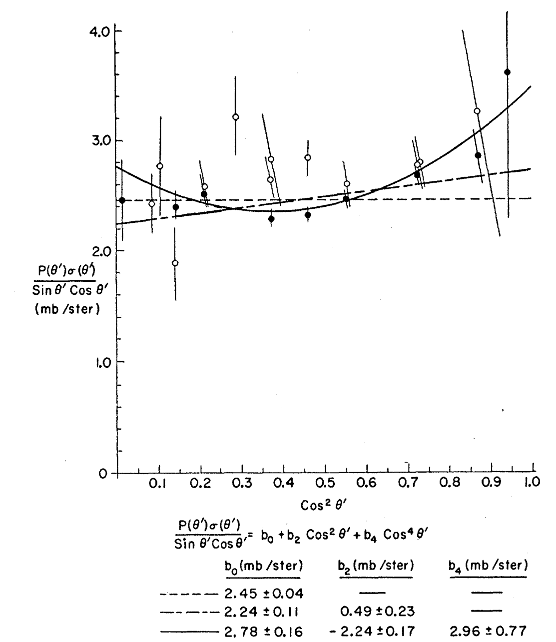

FIG. 4. Replot of Fig. 1, to exhibit departures from pure P-wave polarization effects. The energy is 210 Mev.

count. The measurements at the small angles were therefore repeated and extended with liquid hydrogen, which was also used to obtain data at lower energies.

The full width at half-maximum of the 210-Mev proton spectrum was found to be about 8 Mev, and the true average energies in the several runs did not differ from each other by more than 4 Mev. The spectra of the degraded beams were found to be slightly broadened; the widths at 170 and 130 Mev were 9 and 11 Mev, respectively.

The measured polarizations are given in Table I and plotted in Figs. 1, 2, and 3. Included in the figures for comparison are the measurements[4,2] of Fischer and Baldwin at 170 Mev and of Dickson and Salter at 133 Mev. The curves represent least-squares fits to the data, using one, two, or three parameters as noted. The asymmetry $e_H(\theta_2)$ of second scattering, given as the sixth column in Table I, is the conventional ratio of difference to sum of right and left counting rates for scattering from hydrogen. The corresponding polarization, $P_H(\theta)$, is taken simply as $e_H(\theta_2)/P_1$.

The largest contributions to the uncertainties in the results at all but the smallest angles were statistical in nature. At small angles, the uncertainty in correcting for background became significant. The difficulty arose from the fact that only lower and upper limits to this background, derived from measurements with and without a compensating absorber in the telescope, could be determined. A 0.6% uncertainty in the relative carbon contents of polyethylene and graphite scatterers has been included in the errors. The effects of uncertainties in angular setting, curvature of proton paths, asymmetric target illumination, finite target volume, and telescope solid angle were all well within the quoted errors. In the reduction of data from liquid hydrogen, some small corrections having to do with the construction of the target were required at angles between 40 and 80 degrees; the uncertainties arising from these corrections have been estimated. Not included in the quoted standard deviations of the results is the contribution from uncertainty in the polarization of the primary beam.

TABLE II. Least-squares analysis of the p-p polarization data.

E (Mev)	$\sigma(90°)$ (mb/sterad)	b_0 (mb/sterad)	b_2 (mb/sterad)	b_4 (mb/sterad)	100α
210±4	3.83	2.45±0.04			0.06
		2.24±0.11	0.49±0.23		0.8
		2.78±0.16	−2.24±0.17	2.96±0.77	35
170±5	3.92	1.94±0.06			52
		1.54±0.16	0.82±0.29		88
130±6	4.08	1.55±0.10			0.03
		1.01±0.16	1.05±0.29		17

CONCLUSIONS

The polarization can be written[10] as

$$P(\theta)\sigma(\theta)=\sin\theta\cos\theta\sum_{l=0}^{K}b_{2l}\cos^{2l}\theta,$$

where θ is the center-of-mass scattering angle; $\sigma(\theta)$ is the unpolarized differential p-p cross section; $K=L-1$ for odd L and $L-2$ for even L, where L represents the partial wave of highest orbital angular momentum contributing significantly to the scattering. Measurements[12,13] of the p-p unpolarized differential cross section at 147 Mev and 240 Mev indicate that, within the experimental errors, the scattering in both

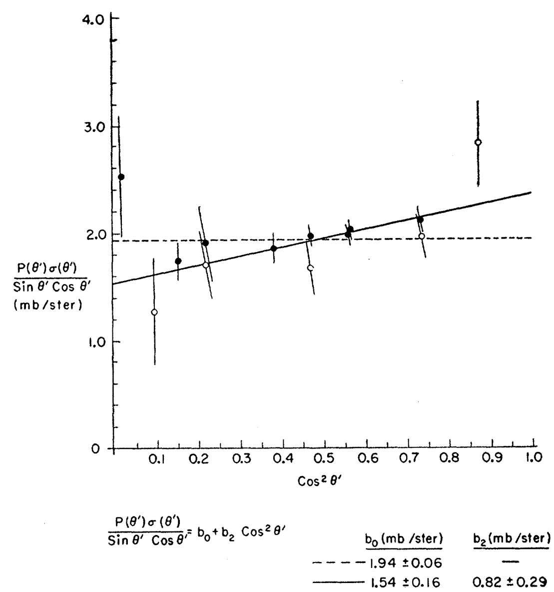

FIG. 5. Replot of Fig. 2, to exhibit departures from pure P-wave polarization effects. The energy is 170 Mev.

cases is isotropic for $\theta>20$ degrees. Therefore, in Figs. 4–6 which give $P(\theta)\sigma(\theta)/\sin\theta\cos\theta$ *vs* $\cos^2\theta$, and in the least-squares reduction of the polarization data to determine the parameters of best fit, $\sigma(\theta)$ is set equal to $\sigma(90°)$. The values of this cross section that have been used are taken from a smoothed interpolation among several experiments[14] and from the measurements of Pettingill.[15] The results of independent measurements[2,4] of the polarization at the two lower energies have also been included in the analysis.

Table II summarizes attempts to fit the data with one, two, or three parameters. The energy uncertainties

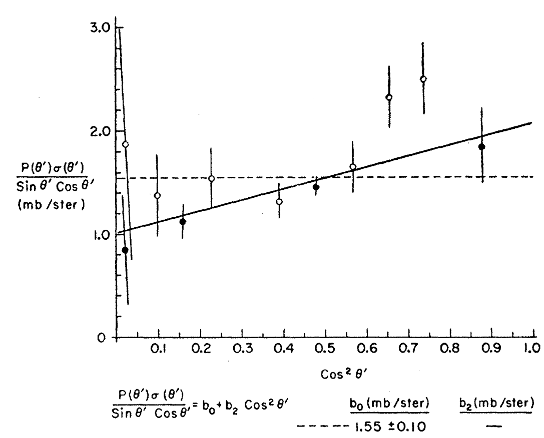

FIG. 6. Replot of Fig. 3, to exhibit departures from pure P-wave polarization effects. The energy is 130 Mev.

[12] Cassels, Pickavance, and Stafford, Proc. Roy. Soc. (London) **A214**, 262 (1952).

[13] C. L. Oxley and R. D. Schamberger, Phys. Rev. **85**, 416 (1952); O. A. Towler, Jr., Phys. Rev. **85**, 1024 (1952).

[14] Summarized by G. Breit, *Proceedings of the Fifth Annual Rochester Conference on High-Energy Nuclear Physics* (Interscience Publishers, Inc., New York, 1955).

[15] G. H. Pettingill, University of California Radiation Laboratory Report UCRL–2808, 1954 (unpublished).

in the first column are taken to be equal to the half-widths at half maximum of the incident proton spectra. The cross sections of the second column were obtained by interpolating existing data, as mentioned above. The next three columns give coefficients b_{2l} and their standard deviations, calculated from least-squares analysis of the data. The results of Fischer and Baldwin at 170 Mev, and of Dickson and Salter at 133 Mev, were included in the calculations. The quantity 100α, appearing in the sixth column, arises from application of the chi-square test to each of the least-squares fits, and represents the percentage probability that an independent measurement will deviate by at least as much from the function of best fit.

An inspection of these results indicates that a description of *p-p* scattering involving *S* and *P* waves alone would be statistically consistent with the data at 170 Mev, where one parameter suffices to give an acceptably large α. However, at the other two energies that have been studied here it appears to be necessary to invoke the *F* wave, a conclusion in agreement with some reported[2,14] previously. The change in the sign of b_2 between 130 and 210 Mev, as well as the increasing significance of b_4 at high energy, can perhaps be explained by consideration of contributions from the $^3F_3$ and $^3F_4$ phases, to which the higher coefficients are sensitive.

We wish to acknowledge the valuable assistance, throughout this work, contributed by Dr. Walter Chesnut, Dr. Sidney Spital, and Mr. Robert Harding. The principal author also thanks the National Science Foundation for its support during part of this research.

PHYSICAL REVIEW VOLUME 106, NUMBER 3 MAY 1, 1957

Changes in the Low-Energy Particle Cutoff and Primary Spectrum of Cosmic Rays*

PETER MEYER AND J. A. SIMPSON
Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois
(Received January 21, 1957)

The low rigidity cutoff for primary particles in the cosmic-ray spectrum reappeared in 1956. From these new results and the earlier measurements in 1948, 1951, and 1954, it is clear that the shift of the low-rigidity cutoff to a very small value is restricted in time to an interval within which solar activity reached a minimum in the 11-year solar cycle. This effect was accompanied by other changes in the primary spectrum; namely (a) the total cosmic-ray intensity and (b) the exponent for the power law spectrum, both passed through maxima near the solar minimum in 1954.

The 1956 results further support the view that these changes in the primary spectrum have their origin in a mechanism controlled by solar activity—most likely the diffusion of cosmic-ray particles through interplanetary disordered magnetic fields transported by plasma clouds of solar origin. If this is so, then only for a brief period near solar minimum is there the possibility of access to the true galactic spectrum for particles below approximately 30 Bv.

I. INTRODUCTION

IN an earlier communication we reported that the primary cosmic-ray spectrum observed at the earth had changed between 1948 and 1951. The changes include a decrease in the energy for the low-energy cutoff, an increase in the total particle intensity, and a change in the power law spectrum extending to higher energies.[1] In addition to these observations, Neher has shown that the low-energy cutoff not only changed but that it may have almost disappeared in the year 1954.[2] Since these effects appeared to be related to the general level of solar activity—the disappearance of the cutoff in 1954 corresponding to minimum solar activity—we have reinvestigated this question by making additional measurements during August 1956, when the level of solar activity had again greatly increased. We wish to report here that the low-energy cutoff has reappeared and is accompanied by further changes in the power law spectrum and total cosmic ray intensity.

We shall discuss briefly the implications of these results for the origin of the low-energy cutoff and the origin of the total intensity variations observed in the solar system.

II. EXPERIMENT

The nucleonic component intensity was measured as a function of geomagnetic latitude at high altitude. As in the case of our earlier observations the apparatus was carried by aircraft. Except for a detector modification which yields twice the counting rate of the 1954 instrument, the experimental apparatus, corrections, and tests were the same as in 1954; further details are given in reference 1.

* Assisted in part by the Office of Scientific Research and the Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, U. S. Air Force.
[1] P. Meyer and J. A. Simpson, Phys. Rev. **99**, 1517 (1955).
[2] H. V. Neher, Phys. Rev. **103**, 228 (1956).