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Polarization of Protons Elastically and Inelastically Scattered in *G*5 Emulsion*†

JEROME I. FRIEDMAN
The Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois
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Measurements have been made of the polarization resulting from both the elastic and inelastic scattering of high-energy protons in Ilford *G*5 emulsion. The elastic polarization was measured by measuring the azimuthal asymmetry of the elastic scattering in emulsion of 0.64±0.04 polarized, 310±5 Mev protons from the University of Chicago synchrocyclotron. The average polarization resulting from elastic scattering between 3° and 15° in the laboratory system is 0.44±0.13. Emulsion was exposed to a 0.76±0.03 polarized, 316±4 Mev proton beam from the Berkeley synchrocyclotron for the measurement of polarization due to inelastic scattering. The light prongs of the stars produced in the emulsion show a definite asymmetry. This asymmetry is increased by requiring of the light prongs an angle-energy correlation consistent with quasi-elastic scattering. The data indicate that the polarization decreases with larger prong number stars. From the 304 meters of track scanned in the measurement of elastic polarization, data have been collected on the cross sections of 305±5 Mev protons in *G*5 emulsion.

I. INTRODUCTION

THE first measurements[1–5] of polarization of high-energy protons caused some discussion as to whether these high polarizations resulted from elastic or quasi-elastic scattering. It was suggested by Fermi that a phenomenological test for elasticity could be applied to polarization measurements in nuclear emulsion. In addition to being able to separate elastic from inelastic events in nuclear emulsion, one is able to observe the inelastic events in great detail. From the prong characteristics of an inelastic scattering in nuclear emulsion, one can, for example, determine roughly the amount of excitation energy deposited in the residual nucleus. It was felt that the possibility of seeing events in detail would perhaps allow one to determine the sensitivity of possible polarization effects to the characteristics of inelastic events.

The measurement of the polarization resulting from scattering was made by measuring the azimuthal asymmetry of the scattering of a polarized beam. If $\sigma_R(\theta)$ and $\sigma_L(\theta)$ are the cross sections for scattering to the right and to the left of the beam respectively, the magnitude of the asymmetry is defined as

$$|\epsilon(\theta)| = \frac{|\sigma_R(\theta)-\sigma_L(\theta)|}{\sigma_R(\theta)+\sigma_L(\theta)},$$

and it can be shown that [6–8]

$$|\epsilon(\theta)| = |P_0P(\theta)|\langle|\cos\varphi|\rangle,$$

where P_0 is the beam polarization, $P(\theta)$ is the polarization resulting from the scattering of an unpolarized beam through an angle θ, and $\langle|\cos\varphi|\rangle$ is the average of $|\cos\varphi|$ over the range of the azimuthal angle of scattering φ.

In this experiment, the measurement made in nuclear emulsion of the distribution of $P(\theta)$ for elastic and inelastic scattering is based on a measurement of the beam polarization made with counters as previously described.[9] Some of the details of the measurement of polarization due to elastic scattering in nuclear emulsion have been previously reported.[10]

II. MEASUREMENT OF POLARIZATION DUE TO ELASTIC SCATTERING

A. Exposure and Scanning

A partially polarized beam (P_0=0.64±0.04) of 310±5 Mev protons from the University of Chicago

* Research supported by a joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
† Based on a thesis submitted to the Faculty of the Department of Physics, the University of Chicago, in partial fulfillment of the requirements for the Ph.D degree.
[1] Oxley, Cartwright, and Rowina, Phys. Rev. **93**, 806 (1954).
[2] Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **93**, 1430 (1954).
[3] Marshall, Marshall, and de Carvalho, Phys. Rev. **93**, 1431 (1954).
[4] J. M. Dickson and D. C. Salter, Nature **173**, 946 (1954).
[5] *Proceedings of the Fourth Annual Rochester Conference on High-Energy Physics* (University of Rochester Press, Rochester, 1954), pp. 5–20.
[6] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949).
[7] J. V. Lepore, Phys. Rev. **79**, 137 (1950).
[8] R. Oehme, Phys. Rev. **98**, 147 (1955).
[9] De Carvalho, Marshall, and Marshall, Phys. Rev. **96**, 1081 (1954).
[10] J. I. Friedman, Phys. Rev. **99**, 1047 (1955).

synchrocyclotron was produced by a 14° scattering of the circulating beam by a beryllium target at a 66 in. radius. The polarized beam entered 600 μ $G5$ nuclear emulsion, which is sensitive to minimum-ionization particles. The emulsion was exposed to a flux of 5×10^3 protons per cm^2.

The emulsion was scanned along the track under a magnification of about 1000 for elastic scatterings between 1° and 15°. These appear as kinks in the tracks with no other observable prongs. Recoil nuclei are not observable.

The mean free path for scatterings between 3° and 15°, where nuclear scattering predominates, is about 100 cm. About $2\frac{1}{2}$ hours of scanning time were required to find a scattering within this angular region. The faster technique of area scanning was attempted but was not found useful because of its low efficiency in detecting this type of event. On the other hand, the efficiency for finding events down to 3° is close to 100% in track scanning. This has been checked by looking at the distribution of right scatterings plus left scatterings as a function of the azimuthal angle of scattering. Deviations from a constant distribution give a measure of the percentage of scatterings missed. It was found that the efficiency decreased somewhat with scattering angle, as would be expected, but that the events missed occurred in a region of azimuth in which the polarization effects are quite small and approach zero.

B. Measurements

When a scattering was found the energy and the polar and azimuthal angles of the scattered track were measured.

The energy was measured to ±10% by grain counting, the error representing the statistics of grain counting and an estimated error in the calibration of the energy-grain density relation. To eliminate the effect of possible variations in development of the emulsion a calibration was made in the vicinity of each event.

The error in the measured scattering angles is estimated to be about ±1.0°.

C. Determination of the Elasticity of Events

Inelastic scatterings in which one or more neutrons come off in addition to the incident proton resemble elastic scatterings in that they appear as kinks in the tracks. These had to be rejected or subtracted from the observed elastic scatterings. Events were rejected in which there was an energy loss as measured by grain counting, greater than that consistent with statistics, namely 30 Mev.

To determine, roughly, what percentage of the remaining scatterings was inelastic another method was used. An examination was made of all two-prong stars which had one prong within 30 Mev of the beam energy and 15° of the beam direction. Hydrogen scatterings were excluded from this group. An event in this group would have been identified as an elastic scattering had a neutron been emitted instead of the slow charged particle. From a measurement of the energy of the slow prong of each such star one can estimate, roughly, from evaporation theory the number of scatterings included in the data which were accompanied by the emission of low-energy neutrons. It is estimated that about 6% of the recorded events fall into this category. The subtraction of this number from the total number of elastic scatterings changes the average value of the polarization in the angular interval from 3° to 15° by less than 0.03.

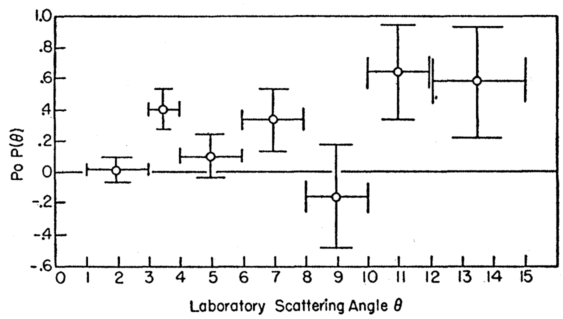

FIG. 1. The quantity $P_0P(\theta)$ shown as a function of laboratory scattering angle for 305±5 Mev protons elastically scattered in $G5$ emulsion. $P(\theta)$ is the polarization resulting from the scattering of an unpolarized beam and P_0 is the beam polarization, 0.64±0.04.

Scatterings in which the recoil nucleus is left intact but in an excited state could not be distinguished from true elastic scatterings in this experiment. However, this effect[11] is expected to be relatively small at small angles.

D. Results

Between 1° and 15°, 471 elastic scatterings were found; 284 of them were between 3° and 15° where nuclear scattering predominates. More than 80% of the cross section for elastic scattering in $G5$ emulsion is due to silver and bromine. These however, are fairly similar in terms of diffraction scattering because their nuclear radii differ only by about 10% and their opacities by about 3%.

In Fig. 1 the quantity $P_0P(\theta)$ is shown as a function of scattering angle. The events are grouped into angular intervals as indicated. The average polarization between 3° and 15° is 0.44±0.13.

Errors are compounded from statistical error and from an uncertainty in the subtraction of inelastic events. The latter is quite small, making less than a 0.01 contribution to the total error.

This experiment gives phenomenological evidence for a high polarization due to elastic scattering, a result in

[11] K. Strauch and W. F. Titus, Phys. Rev. 95, 854 (1954).

good agreement with previous measurements[2–4,9,12] done with counters.

III. MEASUREMENT OF POLARIZATION DUE TO INELASTIC SCATTERING

A. Exposure and Scanning

A separate exposure was made for the measurement of polarization caused by inelastic scattering. A partially polarized beam ($P_0=0.76\pm0.03$) of 316±4 Mev protons from the Berkeley synchrocyclotron was scattered in 1000 μ $G5$ emulsion pellicles.

Most inelastic scatterings in emulsion are stars having two or more prongs and are easily seen and identified. Consequently, the technique of area scanning can be used without sacrificing much efficiency. This technique makes a high track density desirable. An exposure of about 3×10^5 protons per cm^2 was considered optimum since it produced a high density of events in the emulsion without serious obscuration. The tracks were at about 1.6 times minimum, having a grain density of 37 grains per 100μ. Under a total magnification of 200, about one star was found per field of view. Approximately half the stars found were useful for this experiment and were measured.

Since the measurement of polarization is essentially a difference measurement, it is both prone and sensitive to hidden biases. This is especially a problem when the scanner has to reject events. In the previous experiment this difficulty did not arise because the scanner measured and recorded all events found. In this project, however, the measurement of all events found would have required a prohibitive amount of time. The scanners were instructed to reject obviously nonusable events on inspection and to make measurements when in doubt.

To avoid prejudice arising in the scanning procedure, a number of precautions were observed. Before exposure, the pellicles, after having been coded, were randomly scrambled in such a way that neither the author nor the scanners knew whether the markings of a given pellicle corresponded to the left or the right of the beam. The author did not take part in the coding procedure. Only after the scanning project was completed were the orientations of the pellicles disclosed. Scanners were not allowed to look back at previously taken data, and each scanner scanned a few plates. The latter measures were imposed to prevent the scanners from being influenced by what was thought to be a possible trend in the data.

B. Useful Events

Because of the complexity of stars, resulting from the complicated processes that occur in their formation, some classification scheme had to be used in scanning and the recording of data. This classification was essentially dictated by the type of scattering process in which polarization effects were to be measured, a point which will now be discussed.

When a high-energy proton scatters inelastically in a complex nucleus, producing a star, three types of particle emission can occur. First, particles can be emitted directly from quasi-elastic scattering. Secondly, particles are knocked out of the nucleus in complicated cascade processes. Thirdly, a nucleus left in a high enough state of excitation after a collision will emit evaporation particles. The latter two processes would not be expected to give rise to polarization because they would tend to smear out such an effect.

Thus the events sought in this experiment were stars with prongs identifiable as quasi-elastic scatterings. Most of these prongs are light, corresponding to an energy greater than 90 Mev. This is evident from the fact that a proton scattered by a stationary nucleon as far backward as 115° in the barycentric system has an energy of 90 Mev. It was decided to scan only for stars with prongs above 90 Mev because below this energy cascade prongs predominate. Cascade prongs comprise about 75% of all prongs between 30 and 90 Mev, with most of the prongs below 30 Mev being due to evaporation.

Not all light prongs are due to quasi-elastic scattering. Two other processes make some contribution to the production of light prongs.

One of these is meson production. From the meson production cross sections[13] near 300 Mev, one would expect that less than 5% of all light prongs produced in stars are meson tracks. Mesons at minimum ionization could be distinguished from the highest energy protons emitted from stars. Only those mesons emitted in the forward hemisphere between 1.6 and 3.2 times minimum could be mistaken for fast protons. As it is estimated that only 1% of the light stars included in the data involve meson production, this is a negligible source of error.

Some light prongs also result from nuclear cascades. Because cascade processes tend to distribute the energy of the initiating particle among a number of particles, not many high-energy particles would be expected to result from such a process. Those resulting from it are most likely emitted at an early stage of the cascade. In an attempt to eliminate such events, light prongs which could be interpreted as resulting from complicated processes were omitted from the analysis. Light stars with two light prongs coming off on the same side or with a light prong coming off in the backward hemisphere were not included.

Another requirement helps to eliminate light cascade prongs. In quasi-elastic scattering, there is a fairly high angle-energy correlation which only the Fermi mo-

[12] Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **95**, 1105 (1954).

[13] W. Dudziak, University of California Radiation Laboratory Report UCRL-2564, 1954 (unpublished).

mentum prevents from being perfect. By thus requiring some correlation one can purify further the class of quasi-elastic scatterings.

The Fermi momentum of the target nucleons tends to smear out polarization effects because a scattering angle in the laboratory system corresponds to a distribution of angles in the barycentric system. Thus the requirement of correlation also increases the measured polarization because it reduces the width of this distribution.

The data collected from the light stars were the following: the scattering angles and grain count of the most energetic prong of each such star, and an estimate of the energies of all other prongs. These energies were estimated by measuring ranges, gap counts, and grain counts, depending on which method was appropriate. Measurements were made under a magnification of 420. Only light stars having an incoming track within $\pm 3°$ of the beam direction were measured and analyzed.

C. Results

Of 5700 stars found, 2907 had at least one light prong. Of these, 2280 which appeared kinematically simple were measured and analyzed. In Fig. 2 the polarization of the light prongs having an energy within the limits given by

$$E = (E_0 \pm 0.4E_0)\cos^2\theta,$$

is shown as a function of laboratory scattering angle· (E_0 is the beam energy.) In Fig. 3 the polarization of the same group of events is shown as a function of energy. The total number of events included is 1341. Events are grouped into angular intervals as indicated. The errors shown are compounded from statistical errors and the error in the measured value of the polarization of the beam.

The above results indicate that sizable polarizations result from quasi-elastic scattering. This is in good

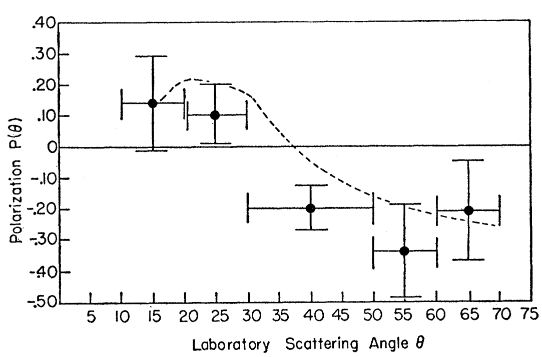

FIG. 2. The polarization $P(\theta)$ of prongs having an energy within the limits given by $E = (E_0 \pm 0.4E_0)\cos^2\theta$, plotted as a function of laboratory scattering angle. The dashed curve is computed from counter work on carbon at 285 Mev [H. Bradner and R. Donaldson, Phys. Rev. **95**, 1701 (1954)].

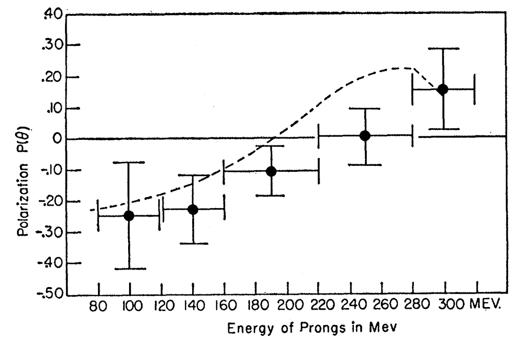

FIG. 3. The polarization $P(\theta)$ of Fig. 2, plotted as a function of energy.

agreement with counter measurements,[14–19] which have given the same results for quasi-elastic scattering at various energies in light elements, namely, D, Li, Be, and C.

To compare the angular distribution of the polarization measured in this experiment with that of the counter results, the relative number of light prongs due to *p-p* and *p-n* scatterings in the emulsion nuclei must be determined. This is because the counter experiments determined *p-p* and *p-n* polarization separately. Since only the fastest prong of each light star was included in the analysis, *p-p* scattering contributes only a small fraction of the light prongs at angles greater than 45° in the laboratory system. These light prongs are mostly due to charge exchange scatterings. The reason for this is evident from kinematics. In a *p-p* scattering, the fastest prong is produced at an angle less than 45°. With the use of the *p-n*[20] and *p-p*[21] differential cross sections at about 300 Mev (the ratio of neutrons to protons in the emulsion being roughly 5 to 4) and the *p-n* and *p-p* polarization curves taken from counter measurements[17] of quasi-elastic scattering in carbon at 285 Mev, polarization curves can be drawn to compare with the results of the present experiment. These appear as the dashed curves in Figs. 2 and 3. The results are in general agreement.

Because about 80% of the cross section for producing light stars in nuclear emulsion is due to silver and bromine,[22] the present experiment indicates that quasi-elastic polarization is the same order of magnitude in relatively heavy nuclei as in light nuclei. One other experiment[18] has given a similar indication. In addition,

[14] Chamberlain, Donaldson, Segrè, and Tripp, Wiegand, and Ypsilantis, Phys. Rev. **95**, 850 (1954).
[15] Marshall, Marshall, Nagle, and Skolnik, Phys. Rev. **95**, 1020 (1954).
[16] Roberts, Tinlot, and Hafner, Phys. Rev. **95**, 1099 (1954).
[17] H. Bradner and R. Donaldson, Phys. Rev. **95**, 1701 (1954).
[18] R. Donaldson and H. Bradner, Phys. Rev. **99**, 892 (1955).
[19] P. Hillman and G. Stafford, Nuovo cimento, **3**, 633 (1956).
[20] J. De Pangher, Phys. Rev. **99**, 1447 (1955).
[21] E. Segrè, Proceedings of Fifth Annual Rochester Conference, (University of Rochester Press, Rochester, 1955), p. 151.
[22] Blau, Oliver, and Smith, Phys. Rev. **91**, 949 (1953).

TABLE I. Efficiency of area scanning.

Number of prongs	Relative efficiency for finding stars (percent)
1	1 ± 1
2	22 ± 3
3	70 ± 10
4	100_{-13}^{+0}
5	100_{-15}^{+0}
6	100_{-15}^{+0}

a measurement[23] has been made of the asymmetry of light prongs of stars in emulsion caused by 570-Mev protons and neutrons. Asymmetries of about 0.10 were observed; but because the beam polarizations were not known, the quasi-elastic polarizations cannot be estimated and compared with the results of the present experiment.

It should be noted that the light stars found in this experiment and, in particular, those used to measure quasi-elastic polarization have a higher average prong number than an unbiased sample of light stars caused by protons of the same energy. This results from the low efficiency of area scanning for finding one- and two-prong stars. This difficulty does not arise in track scanning which has a uniformly high efficiency for all prong numbers. Consequently, the prong distribution for light stars, which was determined from track scanning in the first part of this experiment, was used to estimate the relative efficiency of the area scanning as a function of prong number. The results are given in Table I. In Table II the prong distribution of the light stars found by area scanning is given.

The average prong number of light stars found by area scanning is 3.47 ± 0.04 as compared to 2.30 ± 0.09 from track scanning. It has been estimated that one black prong corresponds on the average to approximately 50-Mev energy transfer to the nucleus,[24] of which 35 Mev goes into thermal excitation.[25] Before these figures can be applied to the data they have to be corrected in order to compensate for the bias of the area scanning of this experiment. This is required for the following reason. For a given energy transfer to the nucleus, there is a prong distribution having a certain average; however, if a scanning bias tends to eliminate stars of low prong number, the measured value of this prong average is higher than the true value. This bias has the effect of decreasing the value of average energy transfer per black prong. After this correction is made, it is estimated that the light stars used in the polarization measurement involve on the average about 45 Mev more energy transfer to the nucleus, 30 Mev going into thermal excitation, than an unbiased sample of light stars.

TABLE II. Prong distribution of light stars found by area scanning.

Number of prongs	Percent of stars	Number of stars
1	0.3 ± 0.1	7
2	$22\ \pm1$	503
3	$33\ \pm1$	752
4	$26\ \pm1$	592
5	$14\ \pm1$	320
6	$4\ \pm0.4$	91
7	0.7 ± 0.2	15

[23] E. L. Grigor'ev, J. Exptl. Theoret. Phys. U.S.S.R. **28**, 761 (1955).
[24] Bernardini, Booth, and Lindenbaum, Phys. Rev. **85**, 826 (1952).
[25] Bernardini, Cortini, and Manfredini, Phys. Rev. **79**, 952 (1950).

This bias tends to decrease greatly the number of true quasi-elastic prongs at angles below 30° in the laboratory system; at these forward angles, quasi-elastic scattering does not transfer enough energy to the nucleus to produce large stars. Consequently, the polarization effects are weakest in this angular region, as is shown in Fig. 4 where the polarization of all light prongs, irrespective of angle-energy correlation, is shown as a function of laboratory scattering angle.

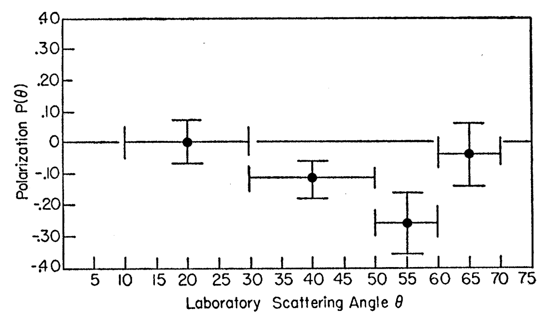

FIG. 4. The polarization $P(\theta)$ of all prongs having an energy greater than 90 Mev.

D. Sensitivity of Polarization to Prong Number

Since the average prong number of stars can be related to the average energy transferred to the nucleus, an examination was made of the dependence of the polarization of the fast prong of a star on its prong number. This was done by grouping the events by prong number and computing the average polarization between 30° and 55° for each group. The results are shown in Table III. The results suggest a decrease of polarization with larger prong numbers. This effect is most likely due to a larger fraction of the 4- to 7-prong stars having fast prongs which result from cascade processes.

An analysis of the polarization of the light stars as a function of their visible energy in prongs below 100 Mev gives the same information as the above analysis. It indicates a decrease of polarization with greater energy transfer to the nucleus.

E. Search for Asymmetry of Black Prongs

Black prongs were also examined for possible polarization effects. This was done to check the assumption that these effects would be smeared out to zero in the processes which produce such prongs. Black prongs are saturated tracks having an energy less than 30 Mev. About 30% of them are emitted directly in cascade processes[24] and the rest are due to nuclear evaporation.

The scanners collected data from all types of stars, recording the number of black prongs to the right and to the left of the beam, irrespective of angle. The black prongs show no asymmetry within the errors of measurement. The measured value of the asymmetry is 0.019 ±0.014.

F. Application of the Technique

The asymmetry measurement[23] in emulsion described above and this experiment demonstrate that inelastic scatterings in nuclear emulsion can be used as a polarization analyzer. This technique could have applications in experiments where counter measurements are impossible or very difficult. To use this technique, a calibration of $P(\theta)$ is required at the energy at which polarization is to be measured. Once this is determined,

TABLE III. Polarization of light prongs as a function of prong number.

Prong numbers grouped together	Average prong number	Average polarization between 30° and 50° in laboratory system
2,3	2.6	-0.24 ± 0.07
4,5,6,7	4.5	-0.09 ± 0.08

a measurement of the asymmetry of light prongs from inelastic scatterings will yield the value of the beam polarization.

One of the most important considerations in using this method is the scanning time required to measure polarization to a given accuracy. Under optimum conditions 10 to 15 light stars can be found and measured per hour. On the basis of this figure and other parameters from the present experiment, an estimate has been made of the scanning time required to measure polarization to a given accuracy at 300 Mev. This is given by

$$t=5.5/\sigma_P^2,$$

where t is expressed in hours and σ_P is a standard deviation. Thus, for example, a polarization measurement to ±0.10 would require 550 hours of scanning.

III. INTERACTION OF 305±5 MEV PROTONS IN G5 EMULSION

In the measurement of the polarization caused by elastic scattering 304 meters of track were scanned, the total length of track scanned being known to ±1%. All interactions found were recorded. From these data may be obtained the elastic and inelastic cross sections of 305±5 Mev protons in *G*5 emulsion. A total of 679 stars, excluding hydrogen scatterings, were found. Scatterings greater than 15° are considered to be inelastic, i.e., one-prong stars. This is justifiable because the number of elastic scatterings beyond 15° is small and is estimated to be roughly equal to the number of inelastic scatterings which are indistinguishable from elastic scatterings at angles less than 15°. Included, also, are 11 zero-prong stars. These appear as stops in tracks.

The mean free path for star production of 305±5 Mev protons in *G*5 nuclear emulsion is thus 44.8±2.3 cm. The extrapolation of the measured differential cross section for elastic scattering down to zero degrees yields a mean free path for total nuclear interaction in *G*5 emulsion of 26.2±2.6 cm. This is to be compared with a mean free path of 25.8 cm, calculated from the total cross section results of Nedzel[26] and de Carvalho.[27] The comparison serves as a check of scanning efficiency.

ACKNOWLEDGMENTS

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[26] V. A. Nedzel, Phys. Rev. **94**, 174 (1954).
[27] H. G. de Carvalho, Phys. Rev. **96**, 398 (1954).