

NUCLEON-NUCLEON SCATTERING AND POLARIZATION

Monday morning, Professor J.R. Oppenheimer presiding.

The first report came from Ashkin, who described the work of R. Sutton and J. Fox at Carnegie Tech. on proton-proton scattering at 437 Mev. The results are shown in Fig. 1, the differential cross sections being given relative to that in 90° (c.m.).

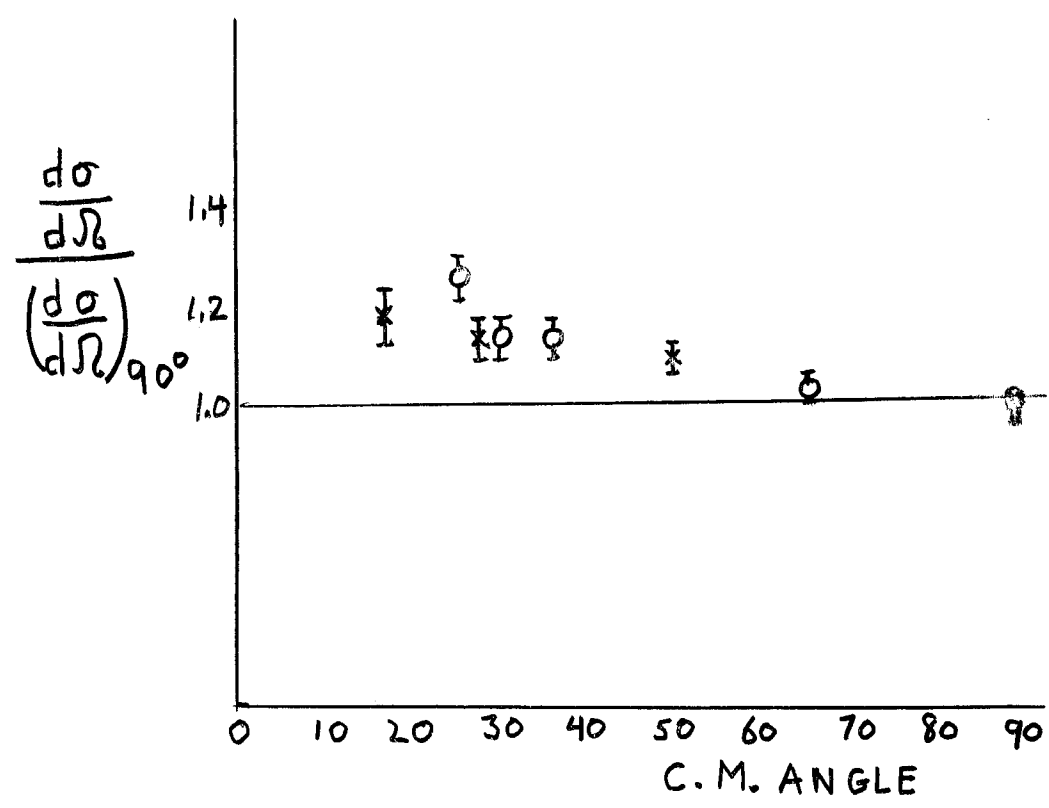


Fig. 1

The circles represent points obtained by measuring two protons in coincidence scattered from CH<sub>2</sub> and C. The crosses were obtained from liquid H<sub>2</sub>, detecting only one of the protons. Where the measurements by the two methods overlap, they are in good agreement. The use of liquid H<sub>2</sub> permitted measurements to be extended down to 10°. There seems to be a definite increase of cross section at small angles, in disagreement with the results from Chicago, where the points of the Marshalls seem to show a decrease at small angles. Oppenheimer asked how, in the Carnegie Tech. experiment, the single-proton measurements excluded inelastic processes. Ashkin described this part of the experiment in more detail (Fig. 2) showing how a copper absorber in the proton telescope was used to take out all but elastic protons, which have the longest range. An ionization chamber monitored the incident beam. The efficiency of the telescope was

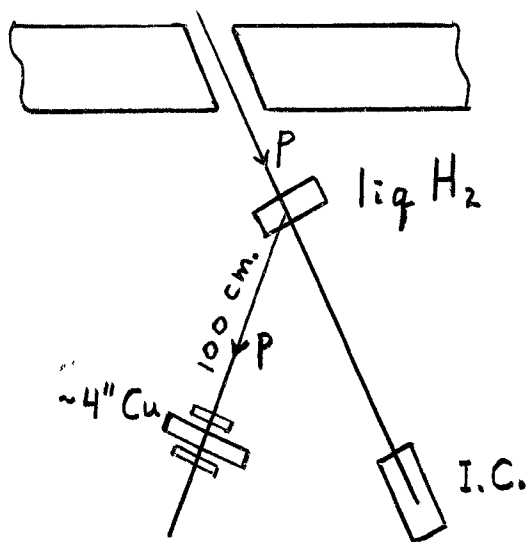
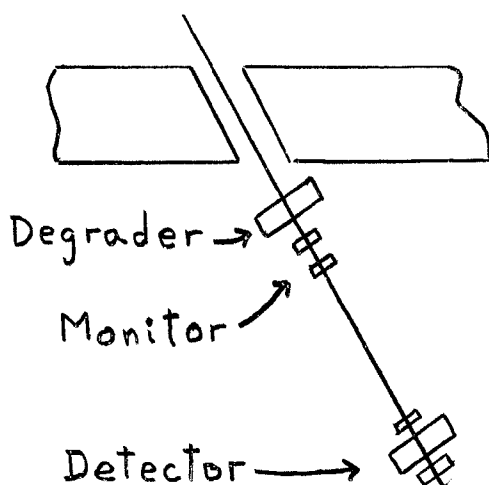


Fig. 2

Furthermore, Sutton and Fox have looked for asymmetries in scattering of this beam at angles around  $10^\circ$  lab, and have found no such effects. J. Marshall pointed out that when one introduces enough copper to reduce 400-Mev protons to the point where the curve begins to drop, the intensity is less than 50% of its original value. This means factor-of-two corrections in the Carnegie Tech. experiment, and the corrections are of course a function of angle. He wondered, therefore, how accurate the calibration of the telescope might have been. Accordingly, Ashkin explained more carefully how the calibrations were made: a copper "degrader" was placed near the shield, its thickness chosen to give protons of an energy equal to that at a given scattering angle. An additional telescope followed this, and served as a monitor against which the



main telescope was calibrated. L. Marshall cautioned that mesons would be produced in the "degrader". (Sutton writes that this effect would be expected to be far too small to cause trouble, and that they have some experimental data to show that there is no detectable meson effect. EMH) The Marshalls suggested that it might be appropriate for them to describe how they carried out their measurement of p-p scattering so as not to include meson

calibrated in the direct beam with an appropriately thicker absorber. Fermi asked whether the incident proton beam used here might have been polarized. Ashkin replied that it could not be polarized, since it came from direct blow-up at  $n = 0.2$ ; in addition, the intensity of the proton beam ( $4 \times 10^6$  p/cm<sup>2</sup> sec) implies that it did not arise from scattering.

production, and Oppenheimer asked them to do so. J. Marshall proceeded to point out that two things were done about this. First, if a meson instead of a proton appeared in the proton counter, it would be expected to be accompanied by a deuteron or proton in the forward direction, so that an anti-coincidence with a forward counter was used to eliminate such counts from the direct counting of scattered protons. Second, advantage was taken of the converse of this: at one scattering angle, coincidences were read between mesons and forward particles, and this result used to measure directly the cross section for meson production. We note that this experiment gives a direct measurement of proton-proton scattering, but that new corrections might easily appear which would be of the same order as the discrepancy now apparent. J. Marshall said that the results of the Chicago p-p polarization experiments (see below) might make necessary a correction to the angular distribution results which would bring them into closer agreement with those of Sutton.

At this point, de Benedetti was asked to give a brief report of the work of Hartzler and Siegel on the angular distribution of n-p scattering at 400 Mev. This research was done at Carnegie Tech.

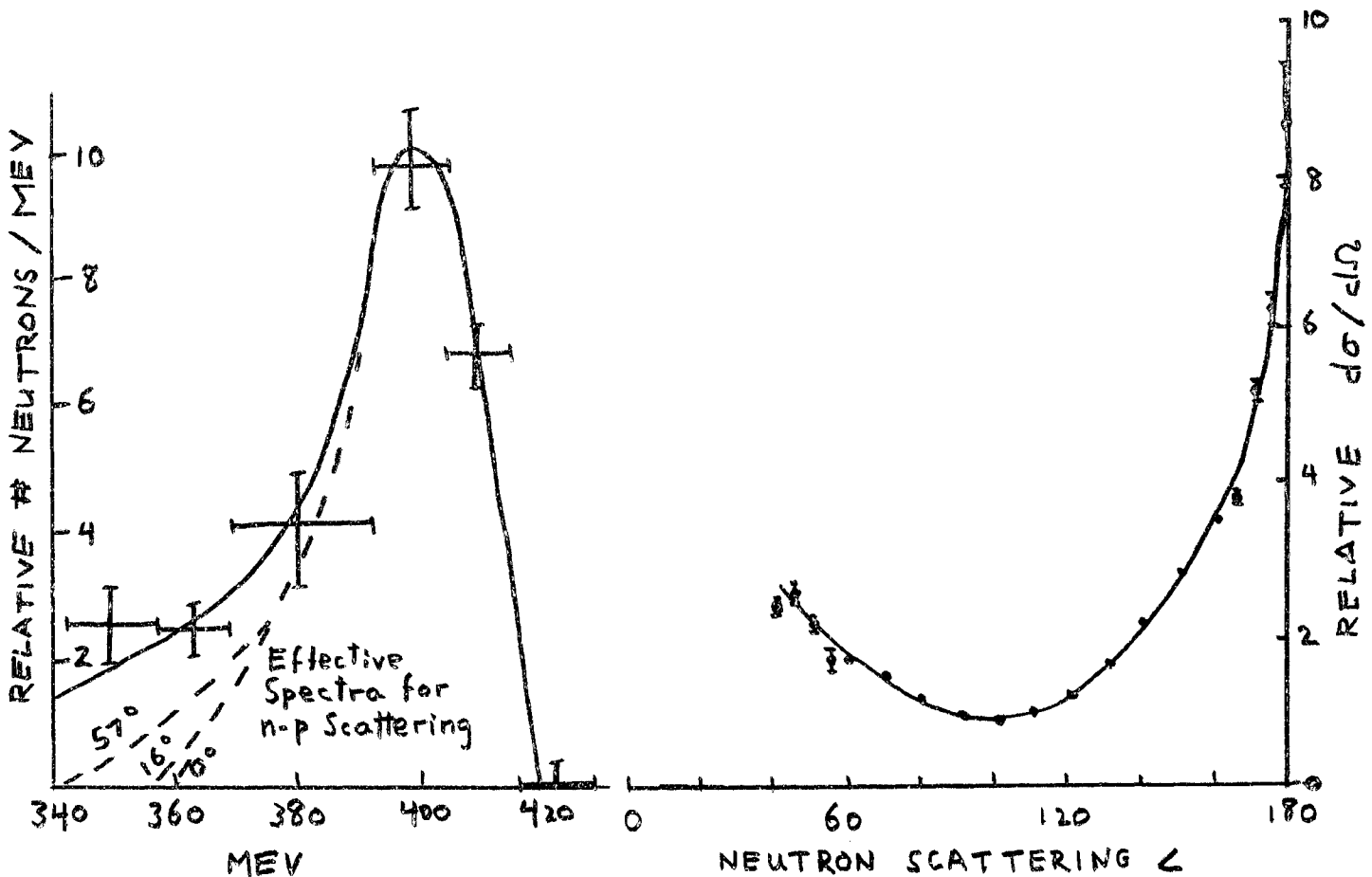


Fig. 3

Fig. 4

The incident neutron spectrum is shown in Fig. 3, together with some of the effective spectra that result from cutting off the recoil proton energies with

a copper absorber. The results of the measurement are given in Fig. 4. The errors shown there are statistical; other known experimental errors have little effect. The minimum occurs at  $100^\circ$  (c.m. neutron angle), and an analysis of the low-angle points carried out after this figure was drawn indicates that they are in fact lower than shown here. An attempt will be made shortly to read forward neutrons in order to proceed farther into the region of small angles. By extrapolating these data to  $0^\circ$ , and using the known absolute total cross section, one finds that the cross section at  $90^\circ$  satisfies the relation with p-p scattering imposed by charge independence. The question was raised as to which total cross section measurement was used in this comparison; Ashkin said that he believes it was the Chicago value. L. Marshall asked whether or not a pion correction had been made in this work. De Benedetti replied that it had, and that the proton beam had been used for this calibration in a manner similar to the method employed by Sutton in the p-p work. Further calibrations were made by observing p-p scattering at several angles, and it was an incidental result of this work that a p-p angular distribution was obtained which checked either Sutton's or the Marshalls' result, depending on whether one procedure or the other was used for meson correction. Moyer mentioned that Powell, at Berkeley, using 300-Mev neutrons in a diffusion cloud chamber, observed a cross section very similar in shape to the one just seen, whereas at 90 Mev the same method yielded symmetry in the center of mass.

Pickavance reported work of R. Wilson at Harwell on n-p scattering at 102 Mev. A liquid scintillation counter was used to detect neutrons, giving

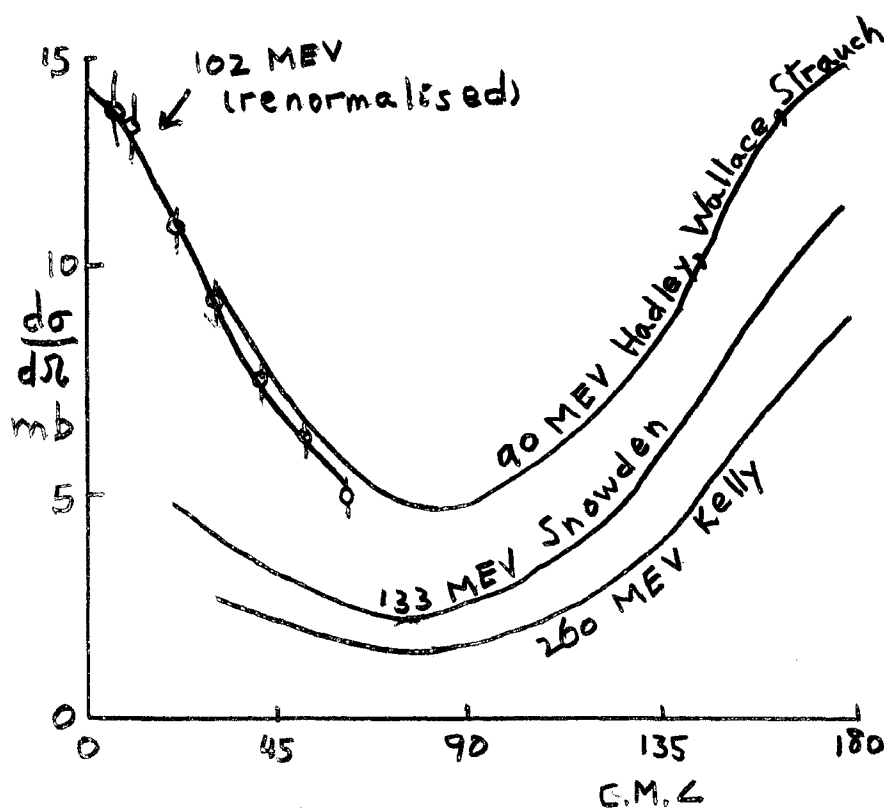


Fig. 5

data in the region of small angles. The results are given in Fig. 5, where comparisons with other experiments are also plotted. What Wilson did was to use the Harwell measurement of total cross section at 90 Mev in order to normalize the old 90 Mev Berkeley data. This may be somewhat wrong, because the Berkeley and

Harwell total cross sections are not in agreement; a better procedure would be to normalize on the basis of effective energy. Clearly, this result is completely agreeable with Powell's cloud chamber data, in that it shows almost perfect symmetry in the center of mass.

Following the discussion of angular distributions, the session proceeded to a series of reports on polarization effects in nucleon-nucleon scattering. (In order to clarify terminology in the discussion that follows, it would be advisable to insert a few remarks regarding the general nature of the polarization experiments. In the event that tensor or spin-orbit forces are significant in nucleon-nucleon interaction, a beam of unpolarized nucleons scattered by a target of unpolarized nucleons will be partially polarized in a direction normal to the scattering plane. The polarization can be detected in a second similar scattering, since the cross section then contains an azimuthal dependence. Polarization effects are zero at second-scattering azimuths of  $\pm 90^\circ$ , while the ratio of intensities at the azimuthal angles  $0^\circ$  and  $180^\circ$  can be written  $\frac{I_0}{I_{180}} = \frac{1 + P(\theta_1) P(\theta_2)}{1 - P(\theta_1) P(\theta_2)}$  where  $P(\theta)$

is the relative polarization in a beam after one scattering through the lab angle  $\theta$ . Azimuthal angle is defined as in Fig. 6. It is conventional to report the results of these experiments in terms of the observed asymmetry of double scattering, written as

$$2e = \frac{2(I_0 - I_{180})}{(I_0 + I_{180})} = 2 P(\theta_1) P(\theta_2).$$

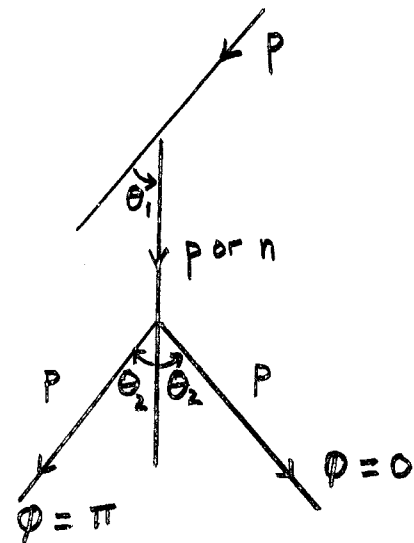


Fig. 6

It is important to note that, if the two scattering processes are identical, the sign of the asymmetry  $2e$  is known a priori to be positive, regardless of details of the theory. It is also clear from symmetry arguments that  $P(0) = 0$  always, and that  $P(\pi/4) = 0$  for the scattering of identical particles. Finally, only the relative sign of  $P(\theta)$  is deducible from the double scattering experiments. (EMH)

Pickavance described an experiment recently performed by Dickson and Salter at Harwell. A primary proton beam whose spectrum was peaked at 150 Mev gave 133-Mev protons after a first scattering from Cu at  $\theta_1 = 20^\circ$ . These protons were taken out through a magnetic channel acting as an energy selector, and scattered from second targets of Cu and H at angles from  $15^\circ$  to  $45^\circ$ . Fig. 7 shows the results of this work, plotting  $2e$  vs.  $\theta_2$ . These data are preliminary, the work

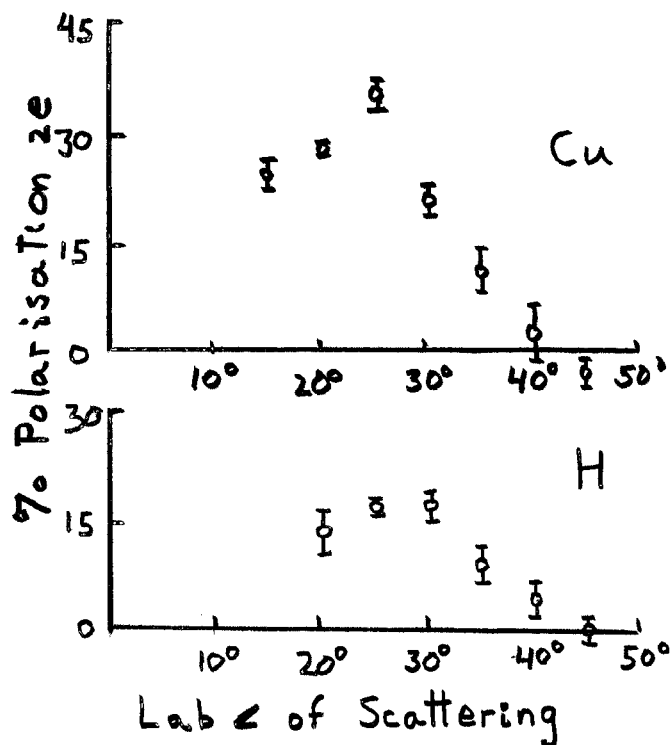


Fig. 7

the distribution is at 150. The magnetic channel, giving good energy definition, is so arranged as to give an emergent beam peaked at 133 Mev, which is just  $150 \cos^2 20^\circ$ . The second target follows suitable collimation, and in the case of H second scatterer, coincidences were taken between two counters at conjugate angles. In the case of Cu second scatterer, a telescope was used containing an absorber whose thickness was calculated, under the assumption that the second scattering is nucleon-nucleon, to give a threshold of 100 Mev in the first-scattered protons. Fermi noted that the  $\sin \theta \cos \theta$  symmetry apparent in these results seems to disappear at higher energy (see below), and Pickavance added that no attempt has as yet been made to pass theoretical curves through these points.

Oxley gave a report on his polarization work, done in collaboration with Cartwright and Rouvina, emphasizing results that have not hitherto been published. He began with a description of the experimental design. A source of 230-Mev primary protons was provided by the Rochester cyclotron (Fig. 8). The first scatterer was an internal target, and first-scattered protons were taken off at a fixed angle of  $19^\circ$  using a collimator in the fringing field.

having been begun at the end of last year, but most of the usual sources of error have been examined with negative results. The asymmetry is seen to be about 40% at  $25^\circ$  with Cu second scatterer, and about 20% at  $30^\circ$  with H second scatterer. Both effects go to zero at  $\theta_2 = 45^\circ$ . Insofar as the angles are comparable, these results agree precisely with Rochester data so far reported. In response to questions from the Marshalls concerning the energy definition in this work, Pickavance gave further details. The maximum proton energy in the cyclotron beam is 164 Mev, but the peak of

The energy of protons entering the second-scattering apparatus covered the interval from 160 to 220 Mev.

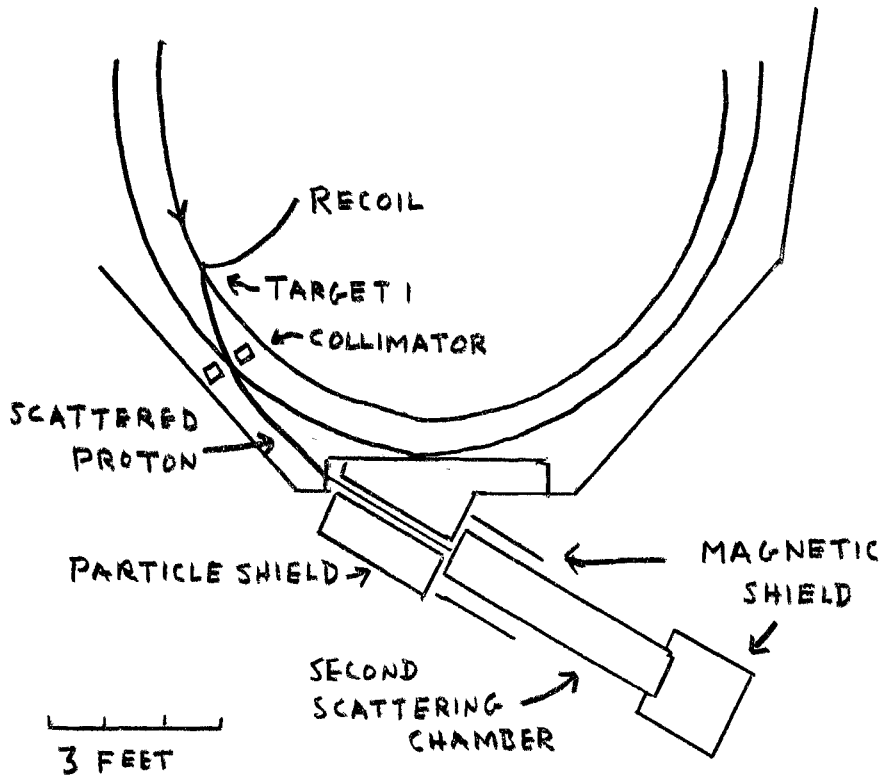


Fig. 8

The second-scattering arrangement is shown in Fig. 9.

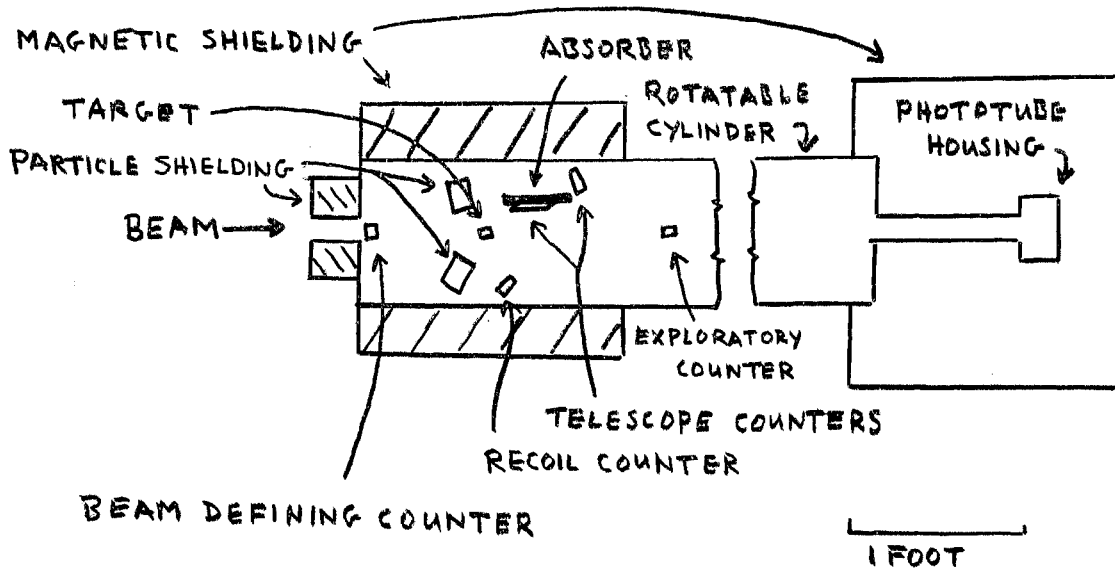


Fig. 9

Measurements were made at a fixed second scattering angle. The beam was defined by a small counter before entering the second scatterer. For the p-p work, the second target was  $\text{CH}_2$  and coincidences were taken between two telescopes at conjugate angles. One telescope contained an absorber which took out protons less energetic than 100 Mev. When other second scatterers were used, data were taken

with only one telescope. The entire second-scattering equipment could be rotated for variation of azimuth. The following data were obtained for two independent runs leading to p-p polarization results, the counts being given as quadruple coincidences per monitor count, normalized to 100 for the average over all  $\phi$ .

	C 1st	H 2nd	CH <sub>2</sub> 1st	H 2nd
$\phi = 0^\circ$	110.8 $\pm$ 1.4	108.6 $\pm$ 1.2	107.1 $\pm$ 1.5	106.3 $\pm$ 1.6
90°	101.0 $\pm$ 1.7	99.4 $\pm$ 2.0	102.2 $\pm$ 2.6	_____
180°	90.1 $\pm$ 1.2	91.4 $\pm$ 1.1	91.6 $\pm$ 1.4	93.7 $\pm$ 1.6
270°	98.8 $\pm$ 1.8	100.6 $\pm$ 2.2	103.4 $\pm$ 2.6	_____

From these data, the asymmetry due to p-p scattering alone can be obtained by CH<sub>2</sub>-C subtraction in the first scattering. The results for the two series of runs are as follows:

1st target	2nd target	Run	2e
C	H	1	20.6 $\pm$ 2.2%
		2	17.2 $\pm$ 1.6
CH <sub>2</sub>	H	1	15.5 $\pm$ 2.2
		2	12.6 $\pm$ 2.2
H	H	1	10.4 $\pm$ 5
		2	8.8 $\pm$ 5
			} 9.6 $\pm$ 3.5

where the errors arise from counting statistics. Then, assuming that, in spite of the small differences in energy and angle in the two scatterings,  $P(\theta_1) = P(\theta_2)$ , we have  $e_H = P_H^2$ , whence  $P_H = 22 \pm 4\%$ . This value can be used, in turn, to obtain values of P for C and other nuclei used as first scatterers. The results, for all targets studied to date, are:

H	22 $\pm$ 4%	C	43 $\pm$ 8%
D	45 $\pm$ 11	Al	21 $\pm$ 8
Li	49 $\pm$ 11	Si	20 $\pm$ 6
Be	49 $\pm$ 11	Cu	44 $\pm$ 11
B	46 $\pm$ 12	Ag	28 $\pm$ 13

where all values hold for proton scattering at 20° in the lab. The measured p-p asymmetry can be compared with calculations carried out by Goldfarb and Feldman on the basis of three different models:

	$2e$
measured	$9.6 \pm 3.5\%$
Christian-Noyes tensor	13
Case-Pais L•S	30
Jastrow hard core	0.5

Commenting on the behavior of these models, Oxley mentioned that the singlet interaction of both the tensor and L•S models give cross sections which pass definitely above experimental results, and that there is not enough Coulomb effect to give an agreement. Thus, on the basis of the differential cross section alone, a modification of the singlet interaction seems to be called for. On the other hand, the Jastrow model, which fits the differential cross section so well, predicts much too little polarization. Finally, Oxley exhibited some checks that were carried out against his experimental procedure. Double scattering was measured from C first and second scatterers, and two runs with different geometry gave  $P_C = 50 \pm 4\%$  and  $36 \pm 3\%$ , to be compared with  $43 \pm 8\%$  from the runs using hydrogen as an analyzer. Similarly, double scattering from Al yielded  $P_{Al} = 24 \pm 4\%$ , to be compared with  $21 \pm 8\%$  from the hydrogen runs. In addition, with C and Al first and second targets, an asymmetry of  $16.4 \pm 4.5\%$  was observed; the prediction from the hydrogen runs is  $18 \pm 8\%$ , while from C-C and Al-Al scattering it is  $17.2 \pm 3.2\%$ . Oxley made some further comments about the polarization effects in complex nuclei. In the first place, one might expect the increase in asymmetry in going from H to D to be the result of a large n-p polarization. However, we must regard the deuteron scattering as a superposition of elastic p-d, quasi-p-p, and quasi-n-p scattering in the approximate ratio 2:1:1. Then the presence of interference effects due to the elastic scattering would vitiate the above conclusion. We must also take into account the results obtained at Berkeley and Harwell on the measurements of n-p polarization. It is important to remember, in so doing, that the n-p experiments involve exchange scattering and therefore tend to work on the high angle region of the  $P(\theta)$  function of Fig. 10, while the n-p contributions to the p-p measurements involve the low angles. In the case of a Serber mixture,  $P(\theta)$  has the type of symmetry shown in Fig. 10. If the function is in fact symmetrical (and there are indications that

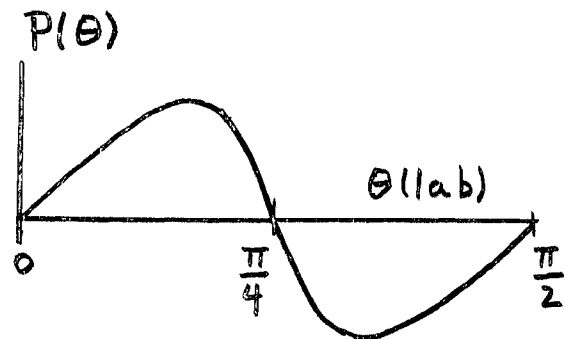


Fig. 10

it is at least approximately so), we must understand why these workers saw n-p effects that were small or, as in the Harwell results, close to zero. If on the other hand the function is asymmetrical, with large values only at small angles, we must understand why the neutron polarization in scattering by complex nuclei is small. Teller inquired as to the relative amount of elastic scattering from the complex nuclei; Oxley said that range curves taken on the protons scattered by C indicated less than 5% elastic, and that this result checked cross sections obtained at Berkeley.

J. Marshall reported on experiments performed at Chicago by J. and L. Marshall on the double scattering of protons using Be for both first and second scatterers. Working at the full energy of the Chicago cyclotron, the Marshalls found after considerable work that they could not detect any polarization effects when they set the energy of the first scattering to correspond to the quasi-free nucleon-nucleon process - i.e., when they selected first-scattered protons with energy computed on the basis of nucleon-nucleon scattering in the Be nucleus. This search was made at  $30^\circ$  (lab) for both angles of scattering. Then, stimulated by news from Segré that he and his collaborators had observed polarization at more forward angles, the Marshalls extended their search in two ways: the internal target was moved to a smaller radius, thereby reducing the primary proton energy from 450 to 337 Mev; and the first scattering angle was set at  $14^\circ$ . They took absorption curves on protons scattered to left and right from the second target, at a lab angle of  $23^\circ$ , and obtained the results shown at the lower left of Fig. 11. The abscissa is the minimum energy accepted by the proton telescope. The presence of asymmetry is evident here; the adjoining figures show the degree of asymmetry,  $2e$ , as a function of threshold energy for four angles of second scattering. At the angles 14, 23 and 30 degrees, it appears that the effect increases with minimum energy of acceptance, and the Marshalls interpret this as meaning that elastic scattering is at least partially responsible for the polarization. Shown in Fig. 12 are asymmetries observed with liquid  $H_2$  as second scatterer. Maximum effect occurs at small angles; the curve is an attempt to describe this situation in terms of states of the angular momentum. One of the advantages of working at the reduced energy of 337 Mev is the accompanying strong reduction of meson background; at 450 Mev the mesons form an appreciable fraction of the count. Finally, Marshall elucidated the bearing that this work has on earlier reports from Chicago regarding the p-p differential cross section. It happened that those data resulted from scattering to the left in the laboratory a beam that had been already scattered to the right in the cyclotron. As a result of the polarization, this method gave cross sections which appeared to decrease as one went

to smaller angles. The measurements were repeated, and averages taken over left and right. The results then appear to be quite flat below  $30^\circ$  (lab), with a cross section of about 4.0 mb/ster. Breit asked whether or not it would be correct to say that unpolarized external proton beams cannot be obtained at Chicago. Marshall said that he believes that inelastic scattering from nuclei at large angles gives a beam in which the polarization is very small.

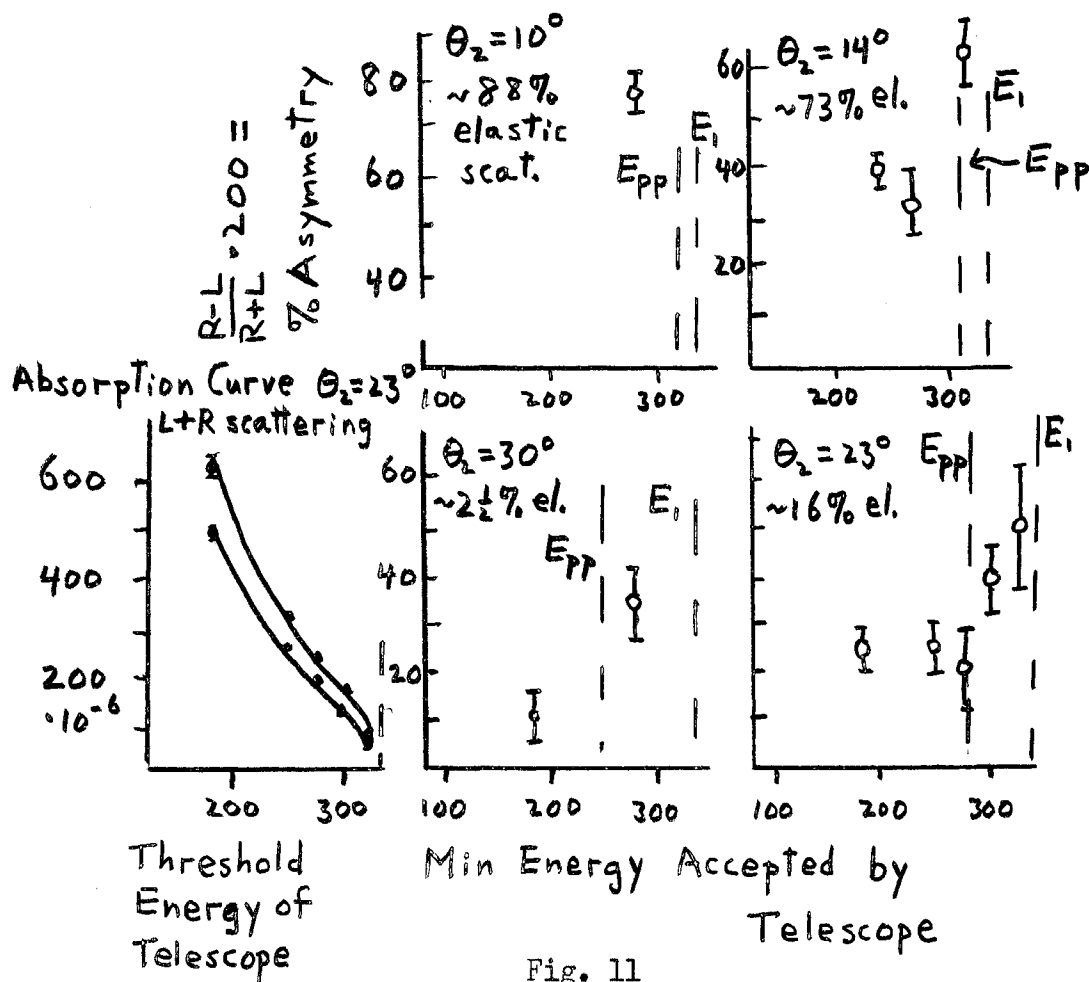


Fig. 11

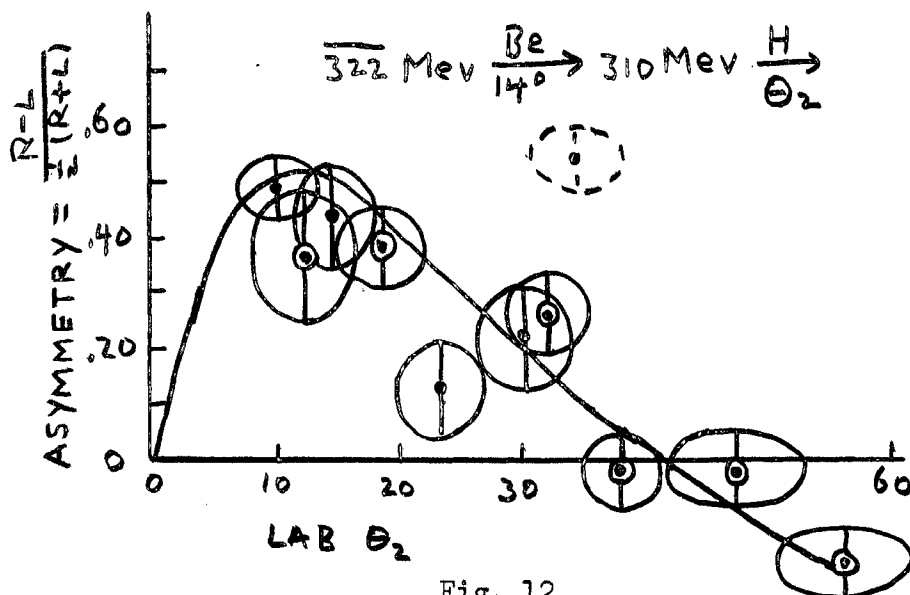


Fig. 12

L. Marshall presented a possible interpretation of the angular dependence of the p-p asymmetry. She began by noting that, although they had found little asymmetry in quasi-nucleon scattering in nuclei at angles between 20 and 35 degrees, they could not say beyond doubt that it did not exist at smaller angles; she regards the correlation to elastic scattering in the Be-Be data as only tentative evidence on this point. She then drew attention to the curve of Fig. 12, which has been drawn by combining results from Berkeley with those from Chicago. Now for an incident beam of completely polarized protons. the differential cross section of p-p scattering can be written

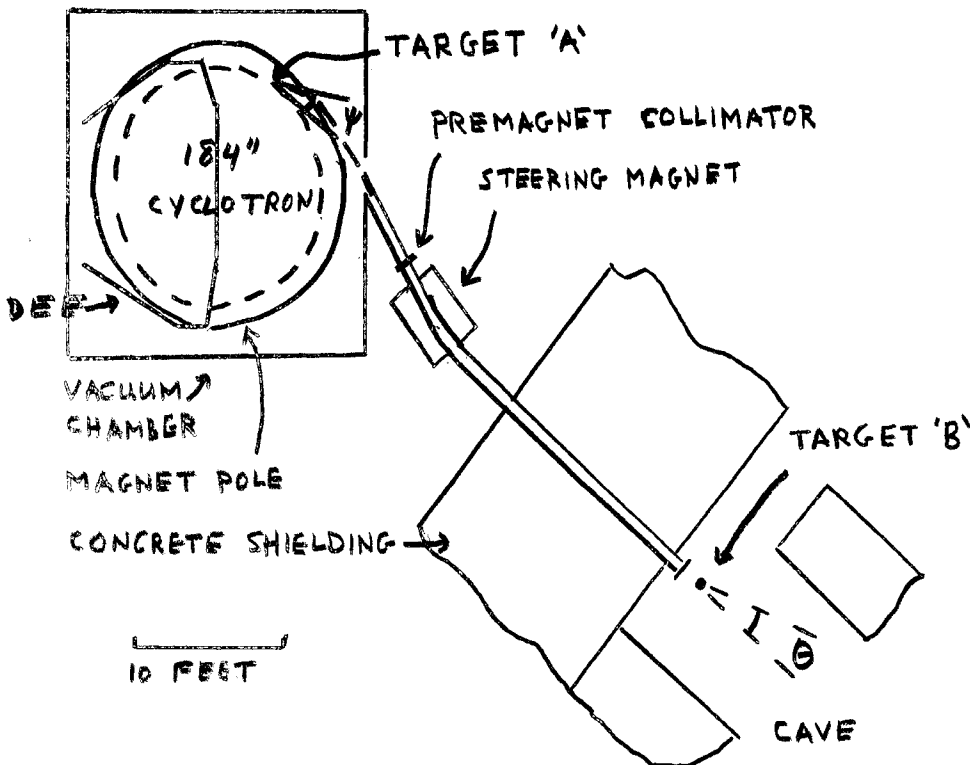
$$\frac{d\sigma}{d\omega} = \sum A_{2n} \cos^{2n} \theta + \sin \theta \cos \theta \sum a_{2n} \cos^{2n} \theta$$

This is true for the states  $^1S, ^3P, ^1D, ^3F, ^1G$ , etc., but only the triplet states contribute to the observed asymmetry. Confining ourselves to  $^3P$  and  $^3F$  states, we can describe the polarization by

$$P(\theta) = \frac{\sin \theta \cos \theta (a + b \cos^2 \theta + c \cos^4 \theta)}{\sum A_{2n} \cos^{2n} \theta}$$

Thus, under these assumptions a plot of  $P/\sin \theta \cos \theta$  vs.  $\cos^2 \theta$  should give a parabola. Working with the available data at high energy, where a departure from the simple  $\sin \theta \cos \theta$  symmetry of the Harwell results seems to occur, one obtains a reasonable fit with coefficients  $a = 0.4, b = -0.8, c = 2.1$ .

Moyer described the Berkeley p-p polarization experiments, performed by Chamberlain and Segré. The internal target, C, and the first scattering angle,  $20^\circ$ , were used without change throughout the work. Fig. 13 is a schematic view of the experiment. At a second scattering angle of  $15^\circ$ , a study was made of



the asymmetry of carbon scattering as a function of absorber thickness in the second-scattered beam. It was then possible to divide the energy into three intervals and to evaluate the asymmetry in each interval, as follows:

Fig. 13

$E_p$	0 - 210	210-280	290 Mev
e	0	$0.37 \pm .04$	$0.46 \pm .04$

Similarly, at a second angle of  $9^\circ$ , the highest interval gave an asymmetry of  $0.43 \pm .02$ . Fermi remarked that these results seemed to be compatible with the conclusion, reached at Chicago, that the asymmetry was entirely the result of elastic scattering; but he had heard rumors that the Berkeley conclusions were different. Teller offered to repeat these rumors: it was his understanding that the Berkeley group had found that the asymmetry was the same (about 0.40) when they looked either at elastic scattering or at events whose energy corresponded to quasi-nucleon scattering. If this were the case, there would be a clear discrepancy between the two conclusions. (This point was not completely clarified in the subsequent discussion, but it is evident from the foregoing information presented by Moyer that Teller's remark correctly summarizes the Berkeley data. For if the primary energy is 330 Mev, a first quasi-nucleon scattering at  $20^\circ$  gives protons at 290 Mev, and a second similar scattering gives 270 Mev. Thus, the 210-280 Mev interval contains these events, and one must go considerably below the quasi-nucleon energy to find a significant drop in asymmetry. L. Marshall feels however that the energy separation may not be good enough to justify the Berkeley conclusions. EMH) The angular dependences of the H and C asymmetries, as measured at Berkeley, are shown in Fig. 14 and 15 respectively. Both go to zero at  $45^\circ$  in the laboratory system.

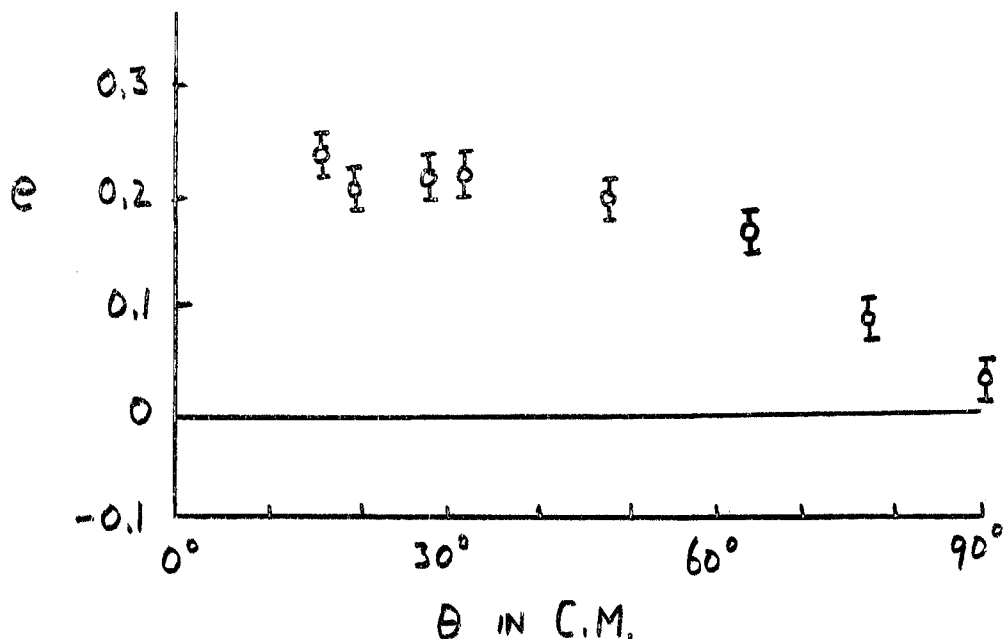


Fig. 14.

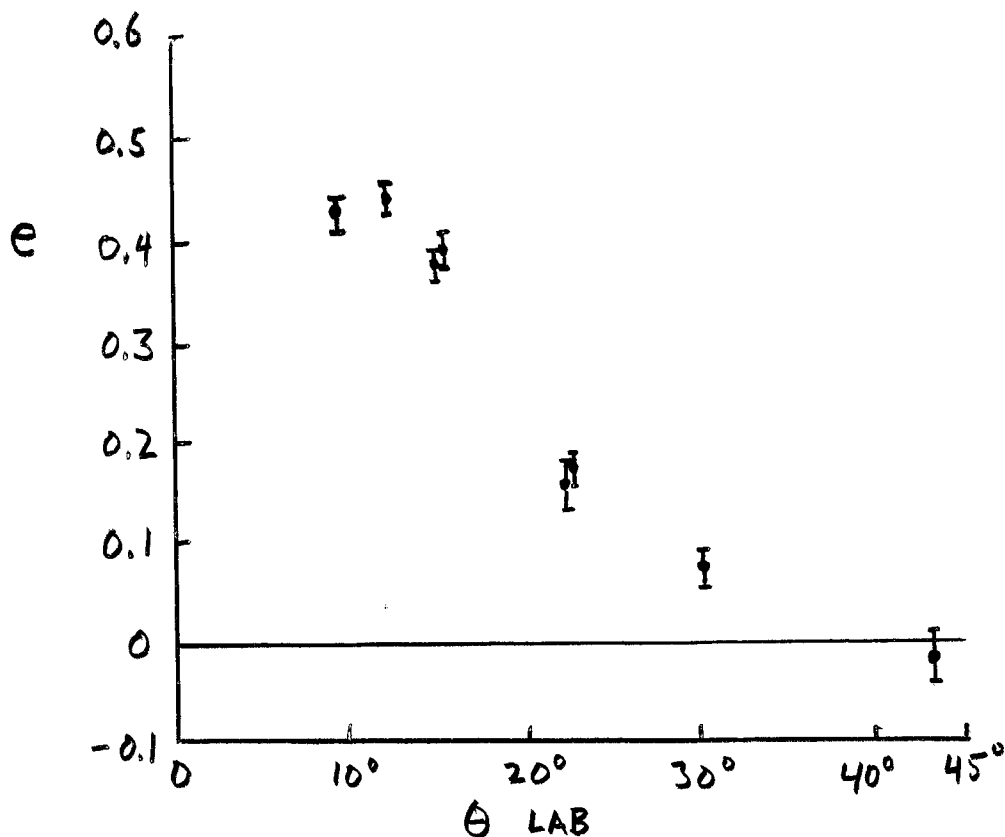


Fig. 15

(The Berkeley group has kindly supplied us with an advance copy of UCRL-2461, comprising a preliminary report on the polarization results referred to by Moyer in the foregoing discussion. Several supplementary points brought out in this report should be mentioned. In the C-C scattering, where an asymmetry of  $0.39 \pm 0.04$  was observed, the corresponding number for the difference of counting rates between azimuths of  $90^\circ$  and  $270^\circ$  was found to be  $0.01 \pm 0.02$ , which is a good indication that the polarization effect is real. It was also found that the external beam, extracted in the ordinary way, showed no asymmetry with either hydrogen or carbon as scatterer. This indicates that the earlier p-p cross section measurements (Chamberlain *et. al.*, Phys. Rev. 83, 923 (1951) were not affected by polarization asymmetry. To these checks were added accurate studies of alignment, geometry, and counter properties, the details of which have not yet been given. Finally, one should note that the Berkeley group reports asymmetries in terms of the quantity  $e$ , rather than the more conventional  $2e$ . EMH)

Moyer also reported on experiment by Bradner on polarization in n-p scattering. The method resembles that of other workers in the sense that the first scattering is a p-n process and the second an n-p. Five internal target positions were available as shown in Fig. 16; those at  $17^\circ$ ,  $35^\circ$ , and  $45^\circ$ , inter-

cepting protons of energy 190, 245, and 340 Mev respectively, produce polarized neutrons along a common direction in the laboratory. A target at  $0^\circ$  is also available, for the purpose of setting equal counting rates in the left and right counters following second scattering.

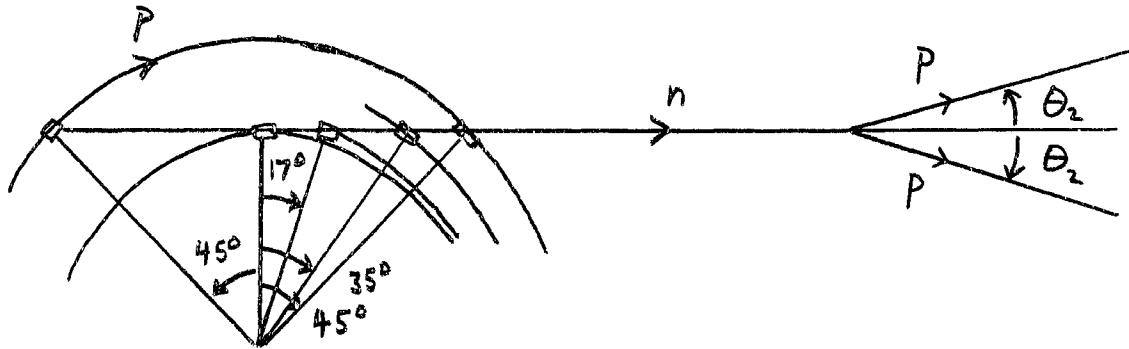


Fig. 16

C and Ta internal targets were used. The second scattering angle was  $25^\circ$ ,  $35^\circ$ , or  $45^\circ$ , and the second scatterer was also C or Ta. The observed asymmetries were as follows:

$\theta_1$	$\theta_2$	targets	$e$
$17^\circ$	$25^\circ$	C - C	$0 \pm 3\%$
		Ta - C	$0 \pm 3\%$
$35^\circ$	$35^\circ$	C - C	$5.2 \pm 2.2\%$
		Ta - Ta	5 - 10%
$45^\circ$	$45^\circ$	Ta - C	5 - 10%

where we are cautioned that the data at  $45^\circ$  are not given with complete confidence.

Hafner presented preliminary results of an essentially similar p-n-p experiment being done at Rochester by Roberts, Tinlot and Hafner. Three features of the general technique should be mentioned: (1) the same recoil telescope is used to observe second scattering on both sides of the neutron beam, its position being referred to an optical centerline by means of an accurately graduated circle; (2) the angular acceptance of the telescope was small ( $\sim 1.5^\circ$ ); and (3) the background was low ( $\sim 5\%$ ). In considering the requisite accuracy of angular settings in this work, one must be aware of the high slopes of C and H differential cross sections for neutron scattering. With an unpolarized neutron beam, one expects asymmetries as high as 20% per degree of error in the centerline, so that accuracy of setting of the order of  $1'$  is desired. Fig. 17 shows how this problem is being handled in the present experiment. A telescope is used to set up an optical centerline intersecting

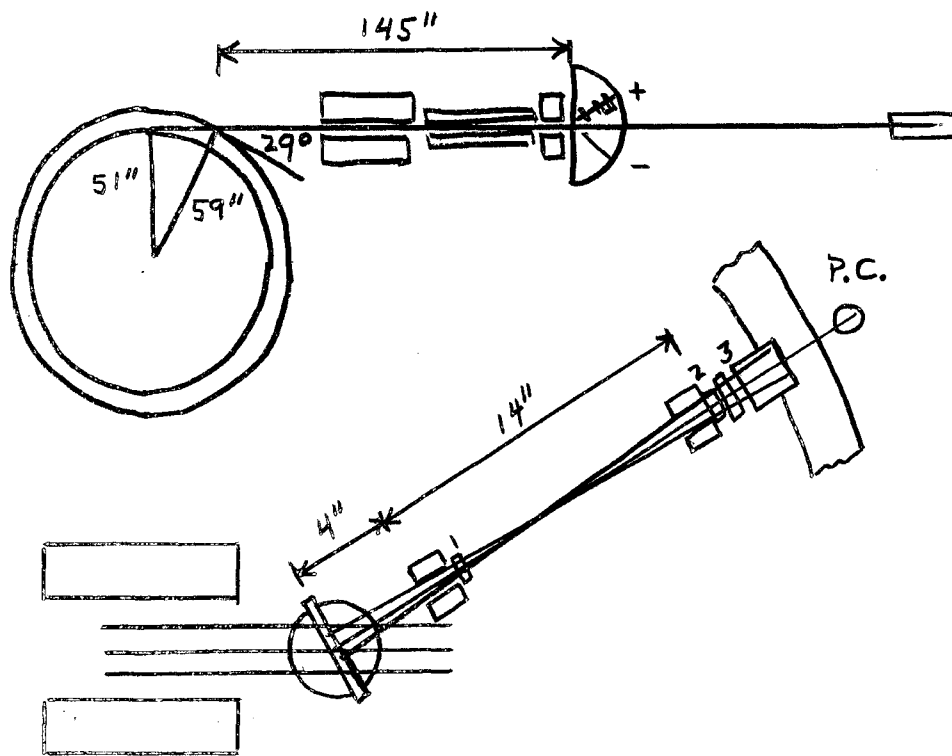


Fig. 17

two internal Be targets. The target at 51" produces neutrons at  $0^\circ$  with respect to the incident protons, and the target at 59" produces neutrons at  $29^\circ$ . The telescope is mounted on a selsyn-driven turntable, and its position is read to  $1'$  with a fixed circle and rotating vernier. The axis of the telescope is accurately defined by two brass

slits, and the reading of the vernier obtained when the slits are coaxial with the optical centerline provides the reference with respect to which the left and right readings are taken. The rotating arm carries a spotlight, and fixed photocells are located at symmetrical angles, so that remote settings of the positions to left and right can be performed rapidly. As a check on the alignment, one should then find that neutrons from the 51" target, which are presumably unpolarized, give zero difference in proton yield from second scattering at equal angles to left and right of the neutron axis. With regard to energy selection in this work, it should be pointed out that the neutron energy from the 29-degree target, assuming free nucleon scattering, is expected to be peaked at about 172 Mev. At each angle of second scattering an absorber is placed ahead of the third counter of the telescope, of such thickness as to stop recoils produced by n-p scattering of 120-Mev neutrons. The preliminary results obtained at second scattering angles of 12, 20, 30, 45 and 55 degrees with second scatterers of  $\text{CH}_2$  and C are given in Fig. 18. The shaded points of the uppermost plot represent the apparent asymmetry,  $2e$ , obtained with the 51" target and  $\text{CH}_2$  second scatterer. These points should all come to zero if the neutrons are unpolarized and the telescope alignment is true. The data in fact seem to show a small rise with angle, with an asymmetry equivalent to an angular error of about  $4'$  at  $30^\circ$ ; this effect is as yet unaccounted for.

(In subsequent runs, evidence has been obtained indicating that this apparent asymmetry may very well be the result of deflection of recoil protons by the reverse fringing field of the cyclotron, which is about 100 gauss at the telescope. EMH) The asymmetry observed with 29-degree first target and CH<sub>2</sub> second target, as a function of second scattering angle, is also shown in the uppermost curve, plotted as open circles. The effect of polarization appears to be statistically significant (standard deviations of number of counts are shown in these plots). The C effect, and

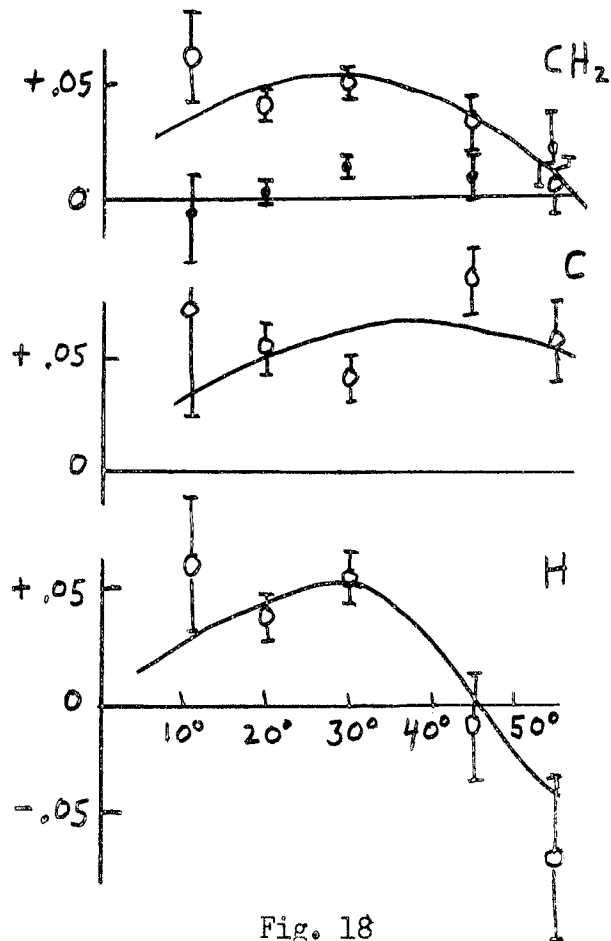


Fig. 18

the H effect obtained by CH<sub>2</sub>-C subtraction, are shown in the middle and lowest plots respectively. The principal feature to which attention should be drawn here is the difference between the C and H angular dependence, the former remaining positive to 55°, the latter going negative at ~45°. Swanson (Phys. Rev. 89, 749, 1953)) has calculated  $P(\Theta)$  in high energy n-p scattering, combining the central and tensor potential of Christian and Hart with the "half-exchange" dependence suggested by Serber. The latter feature of the theory gives interaction only in orbital states of the same parity, and as a consequence  $P(45^\circ) = 0$ . The H curve of Fig. 18 has the shape predicted by Swanson. Since the degree of polarization of the neutron beam is not yet known, the magnitude of the asymmetry cannot be checked against this theory. If we assume free nucleon scattering in the first target, however, we find that the measured effect is about half of the prediction. In comparison with other n-p experiments, it is notable that Wouters (Phys. Rev. 84, 1069 (1951)), using LiD and LiH first targets and a neutron energy of about 250 Mev, found rough experimental agreement with the shape of Swanson's theoretical curve. On the other hand, Dickson and Salter, (Proc. Phys. Soc. A66, 721 (1953)), using Be first scatterers, a neutron energy of 135 Mev and fixed scattering angles of 20°, report no significant asymmetry (~2%) in hydrogen. This result is not necessarily in contradiction with the present experiment if one takes into account their lower energy and larger errors. (Later runs on the Rochester

experiment gave a C-C asymmetry of  $10.2 \pm 2.0\%$  at a second angle of  $30^\circ$ . This is in good agreement with Bradner's result at the same energy and approximately the same angles, which is  $2e = 10.4 \pm 4.4\%$ . (EMH)

At this point, prior to a discussion of the theoretical significance of the results so far reported, Bernardini asked Oppenheimer if he would be good enough to "synthesize" the experimental information on polarization. Oppenheimer accordingly gave a summary comprised of what he believed to be the significant facts: (1) in the p-p scattering there appear to be very large polarization effects which increase with energy; (2) symmetry of type  $\sin \theta \cos \theta$  may obtain at the lower energies, but there is little chance that it remains at the higher energies, where it appears that states higher than  $^3P$  must be involved; (3) in the exchange n-p scattering, the polarization effects seem to be somewhat smaller, and also to increase with energy; (4) the extent to which the neutron experiments so far performed represent nucleon-nucleon as opposed to nucleon-nucleus effects is not clear; (5) there also seem to be polarization effects when protons are scattered by nuclei, and whereas the Chicago results indicate that these effects are probably larger than the p-p effects, the Berkeley results suggest that they are "not certainly larger". When asked whether or not the last statement contained the essence of his earlier remarks, Teller replied that the statement was "perhaps not wrong, but certainly unrecognizable". This led Oppenheimer to rephrase the point in the form of a question: at fairly high energies (around 350 Mev), what are the relative polarization effects in two types of scattering, the first of which can be regarded as the double scattering of a proton from each of two nucleons in turn, and the second of which can be regarded as having involved an entire nucleus in at least one of the scatterings? Then, repeating his former statement, Oppenheimer said that it seemed, from the Chicago report, that as one shifted the detectable energy of second scattering to a region that could not be reached by nucleon-nucleon scattering the asymmetry increased, whereas it seemed from the Berkeley report (as interpreted by Teller) that this shift had little or no effect on the asymmetry.

Oppenheimer asked Teller if he would not elaborate upon his opinion of this matter, and Teller proceeded to do so. He said that it is certainly clear that facts (1) and (2) of Oppenheimer's summary reflect the experimental facts in an accurate way. But he felt that it is also quite clear that protons scattered by nuclei, or at least by some nuclei, can be polarized from 2 to 5 times as strongly as they are in p-p scattering. So the first important question facing us concerns what this effect may be due to. The next experimental fact, on which there is general agreement among the various workers, is

the smallness of polarization in exchange scattering; this is Oppenheimer's point (3). In considering the reasons for large polarization in nuclear scattering of protons, Teller believes there are at least two possibilities. It may be that the properties of nucleons are changed by being bound into nuclei. Or it may be the presence of neutrons in complex nuclei that enhances the polarization. This statement need not, as it appears to, contradict the observation that exchange polarization is small. In fact, it may very well be that one observes a small exchange polarization and (perhaps without meaning the word too literally) therefore a large non-exchange polarization. Finally, it may be that the scattering from complex nuclei involves the nuclear field as a whole, rather than a superposition of nucleon-nucleon effects. There need not then be any simple correlation between nuclear and nucleon effects. As to the discrepancy between the Berkeley and Chicago experimental results on nuclear scattering, Teller felt that the point hinges on the measurement of rather small energy losses, and that expert criticism will have to be brought to bear on the feasibility of drawing significant conclusions in the present state of the experiments. A crucial question that will remain with us concerns the possibility that the energy loss associated with nucleon-nucleon collisions can materially reduce the polarization.

Oxley remarked that, in the Rochester p-p experiments, the possibility of elastic scattering was certainly ruled out (see Oxley's earlier remarks). Oppenheimer noted that, even disregarding polarization effects, it is not yet experimentally clear what the relative contributions of the two types of process are, and that careful studies of energy loss are needed. Strauch pointed out that such studies are being carried out at Harvard, with the conclusion that very little of the scattering of high energy protons by light nuclei need be truly elastic. Considerable inelastic scattering at 96 Mev has been observed. Further discussion of this was deferred to the afternoon session.

Breit brought up the idea, which used to be discussed in connection with electron polarization, that appreciable depolarizing effects might result from multiple scattering. Thus, if there is in fact appreciable inelastic scattering of high-energy nucleons, one wonders if multiple scattering of nucleons within nuclear matter would depolarize them significantly. Has this effect been estimated? Hafner said that this is the usual way of stating that exchange polarization might be weaker than you would otherwise expect.

Breit presented a discussion of some general features of the theory connected with two nucleons. We know in fact very little about potentials other than the  $^3S$  potential of the deuteron and the  $^1S$  potential in the p-p and n-p systems. It is clear from high-energy scattering that S-waves alone

cannot account for the observations; this point was emphasized in today's results, and it was even concluded from the Chicago polarization results that angular momentum greater than one is required. But when, in reviewing experimental data of this kind, we fix our attention on special potential models, we are probably not being fair either to the experimental situation or to the model. It is difficult to believe that, at an energy of 400 Mev, the picture of a static potential holds very well. We are working on a sounder basis when we confine ourselves to phase shifts; there is then simply an implicit dependence of the Hamiltonian (or part of it) on an interaction between spins and coordinates, the details of this interaction being largely unknown. Perhaps one thing that can be said is that the  $(\sigma, r)$  interaction is smaller than assumed, for example, in the Christian-Noyes theory. Perhaps we should consider for a moment how the phase shifts are connected with the experiments. We recall certain theoretical work, particularly that of Ashkin and Wolfenstein, in which the total intensity of scattering is written as  $I = \text{Tr}(MM^\dagger) + \text{Tr}(MM^\dagger \underline{\sigma} \cdot \langle \underline{\sigma} \rangle)$  where  $M$  is the scattering matrix,  $\underline{\sigma}$  the spin matrix, and  $\langle \underline{\sigma} \rangle$  the mean value of the spin of the incident beam. Thus, if the mean incident spin is not zero, the second term  $I$  is a contribution that depends on the spin orientation. The theory can be used to derive cross sections and polarization asymmetries in terms of phase shifts  $\delta_L^J$ . For instance, if the scattering involves only S- and P-waves ( $L \leq 1$ ), and we confine ourselves to the p-p system, the polarization is given by

$$P(\theta) = \frac{\sin 2\theta}{k^2 \sigma(\theta)} \left[ 3 \sin \delta_0^0 \sin \delta_1^2 \sin(\delta_1^0 - \delta_1^2) + \frac{a}{2} \sin \delta_1^0 \sin \delta_1^2 \sin(\delta_1^0 - \delta_1^2) \right]$$

In view of the appearance in this expression of differences between P-wave phase shifts, we know that the experimental observation of polarization effects implies the existence, not only of P-wave effects, but of some kind of spin-orbit coupling as well. Naturally, we do not learn anything from the phase shifts about the explicit form of the spin-orbit dependence of the Hamiltonian. As to the fitting of the experimental data with four phase shifts, Garren (Phys. Rev. 92, 213 (1953)) has carried out such a program, taking into account both the p-p cross section and the polarization data up to 240 Mev. No such attempt has been made at higher energies; presumably, from the Chicago work, higher angular momenta must be involved in this region. In making the lower-energy fit, one can also satisfy the requirement of charge independence as well as the requirement that the P-wave phase shifts correspond to potentials in which the order of the P levels is inverted. This latter requirement, which might be imposed on the basis of the observed spectroscopy of complex nuclei, implies that  $\delta_1^2$  be less than  $\delta_1^0$ , and we notice that all of Garren's fits to the

240-Mev p-p data satisfy this condition. It is not maintained that the order must be this way, for that would imply more faith in explicit potentials than we are justified in having at this time. Wentzel remarked that one should at least treat the quadrupole moment of the deuteron in the same way. Breit confessed that he is rather critical of the usual descriptions of the quadrupole moment, on the grounds that a gradual velocity dependence of the depth of potential may affect the range, and consequently the admixture of states. Feynman asked whether or not it is worthwhile to worry about the fact that the phase shifts may be complex, considering the meson production. Breit suggested that this should be done at higher energies, but ought not to be important at 240 Mev.

An additional refinement in the treatment of the p-p data is possible. Observing that the states of the system are  $^1S_0$ ,  $^3P_{0,1,2}$ ,  $^1D_2$ ,  $^3F_{2,3,4}$ , etc., one might assume that the  $^3P_2$  and  $^3F_2$  states are coupled. This possibility has been examined by Breit and his collaborators\* by regarding such a coupling as the result of a resonance at high energy; the precise location of the resonance turns out not to be important in fitting the data. It was found that charge independence, as well as the inverted order of P states, are consistent with this treatment, and imply a limit to the strength of the coupling constant. As far as can be seen, the limit is not stringent enough to prevent the introduction of the F-wave effects suggested by the Chicago data. Fermi asked whether or not there is a consistency among the several potential recipes with regard to the sign that they predict for the polarization. In answer to this, Feldman reported that the sign cannot be given in the Jastrow model. In the singular tensor modification of the Christian-Noyes model, one sign gives a better fit to the unpolarized differential cross section than the other. In the spin-orbit model, the fit to unpolarized data is bad for either choice of sign.

The session continued with a discussion of nucleon interactions leading to the production of pions. Ashkin presented Sutton's data on the differential cross section for  $P+P \rightarrow D+\pi^+$  at  $437 \pm 2$  Mev. The geometry of the measurement is shown in Fig. 19. The proton beam was monitored with an ionization chamber, which was followed by a target of liquid  $H_2$ . Coincidences were taken between pion and deuteron. The pion counter, located about one meter from the target, defined the geometry. The deuteron counter had to be placed close to the direction of the incident beam, since the maximum deuteron angle in this experiment is  $9^\circ$ . The deuteron counter had therefore to be placed at a somewhat greater distance than the pion counter; it also had to be sufficiently extended to cover deuterons multiply scattered in the

\*R.M. Thaler and J. Bengtson

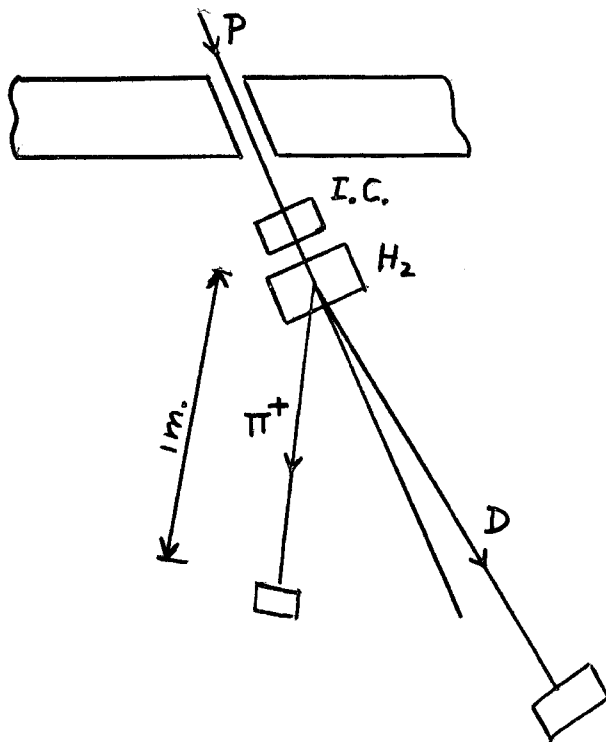


Fig. 19

counter fixed, the yield of pions vs. angle exhibited a good peak; and it was found that the peak occurred at the angle expected from the kinematics. Another argument for the deuteron reaction followed from the fact that, when the deuteron counter was moved in to about half the distance, the counting rate was unchanged. One would have expected, if the protons were being counted,

target. Deuteron time-of-flight could be measured to about 10%, but it happens that protons from the competing reaction  $P + P \rightarrow P + N + \pi^+$  have about the same velocity, so that further evidence on the amount of competition was needed. Analysis of the ranges of particles entering the deuteron counter showed that the proton contamination was less than 10%. Further evidence that a two-body process was primarily involved came from the observation that, with the deuteron

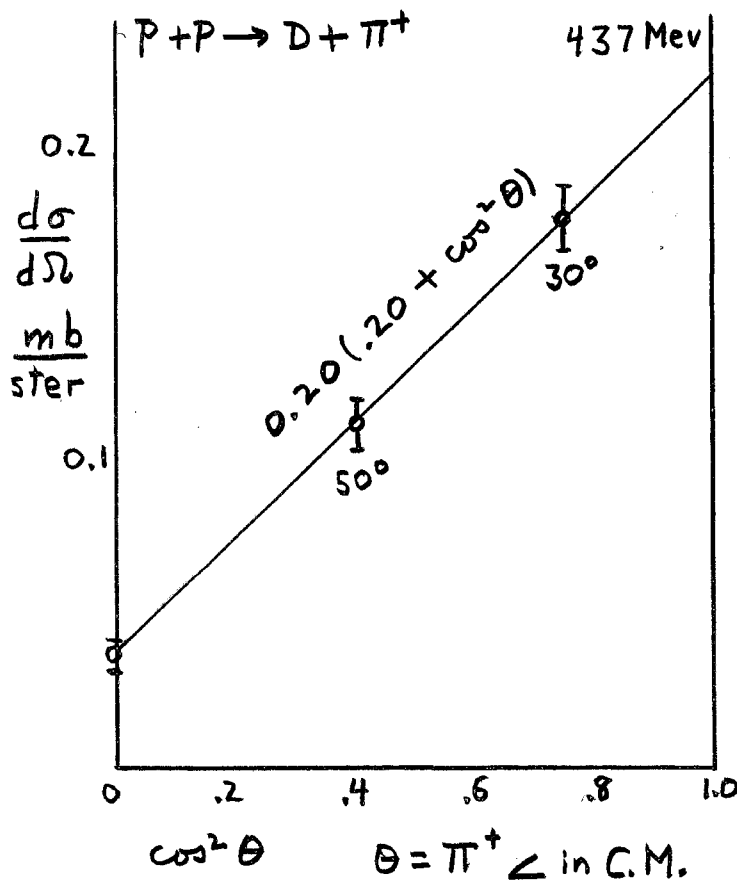


Fig. 20

that this part of the counting rate would have increased by about a factor of four. The data of this experiment (Fig. 20) when corrected for  $\pi^+$  decay indicate a differential cross section that can be well fitted by  $0.20(0.20 \pm 0.02) + \cos^2\theta$  mb/ster. giving a total cross section of  $1.35 \pm 0.13$  mb. Ashkin compared this result with the inverse process as measured by Steinberger at pion energies of 25, 40, and 50 Mev. Sutton's pion energy was 62 Mev; extrapolation of Steinberger's data predicts a total cross section of 1.2 mb.

Commenting on the apparent discrepancy between Sutton's point at  $90^\circ$  and the Chicago result ( $0.16 \text{ mb/ster}$ ) at about  $80^\circ$ , L. Marshall noted that the geometry of the latter experiment was such as to include both competing processes. Fermi pointed out that Rosenfeld at Chicago has measured the relative probabilities of the two processes at about 420 Mev and finds that their ratio is about 1:1. He also finds that the excitation function checks quite closely with a theory of Watson which assumes a matrix element proportional to the momentum of the pion. However, this theory predicts a somewhat smaller probability for the process in which the two nucleons come out unbound than the experiment seems to indicate.

Moyer reported the work of R. Madey, K. Bandtel, J. Frank, and B.J. Moyer on the reactions  $p + d \rightarrow H^3 + \pi^+$  and  $p + d \rightarrow He^3 + \pi^0$ . The assumption of charge independence requires that the ratio of yields for these two reactions should be 2:1, with the same angular distribution. The first reaction was fairly carefully studied, using 2"x2" pion detectors 1.2 ft. from the target at  $110^\circ$  to the 340-Mev proton beam, and 2"x4" triton detectors at 11 ft. and  $8^\circ$ . The long triton path (which is made possible by the fact that these particles are concentrated in a forward cone) permitted good time-of-flight measurements (Fig. 22). The 149-Mev tritons took the longest time and were clearly resolved from 85-Mev

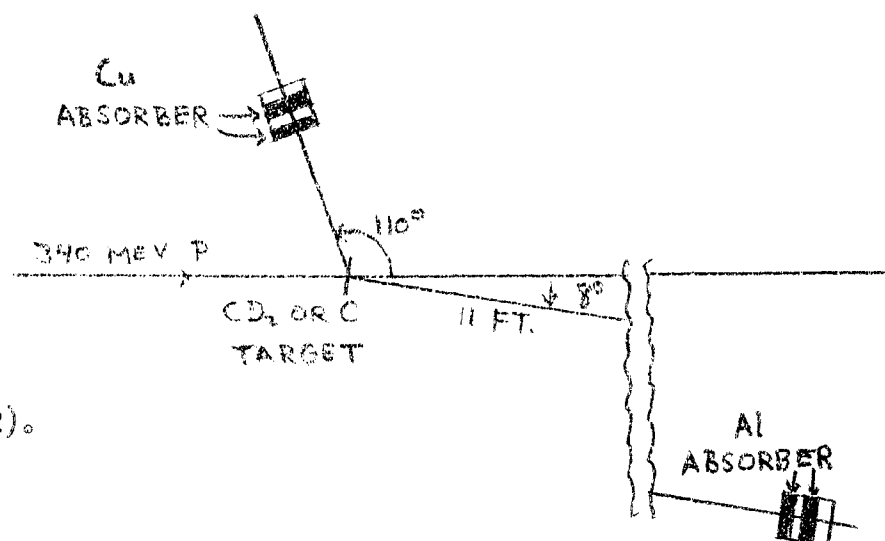


Fig. 21

protons, the nearest competitor. The pion signal was delayed to match the triton, the coincidences were counted. The differential cross sections are shown in Fig. 23. Ruderman and Bludman have examined this process theoretically, starting from the reaction  $p + p \rightarrow d + \pi^+$  and adding the requirement that the deuteron pick up a neutron. When the momentum distribution in the deuteron is taken into account, this model predicts the cross section shown as the uppermost smooth curve in Fig. 23. The fit is poor. As one of the several possible ways of improving the fit, these workers have included a hard core in the model, and achieve an excellent agreement with the experiment when the core radius is taken as 0.50 pion Compton wavelength. For the  $\pi^0$  yield, the results are not yet clear.  $He^3$  particles have probably been seen, and the ratio of yields seems to be between 1.5 and 2 to 1. The proce-

dure involves the difference in  $dE/dx$  for  $He^3$  and  $H^3$ .

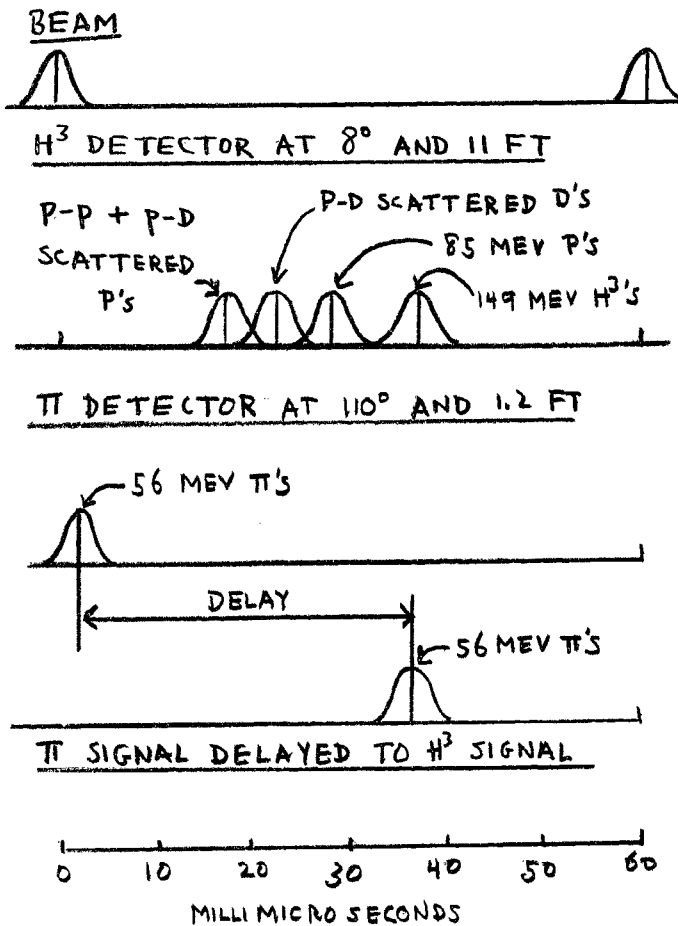


Fig. 22

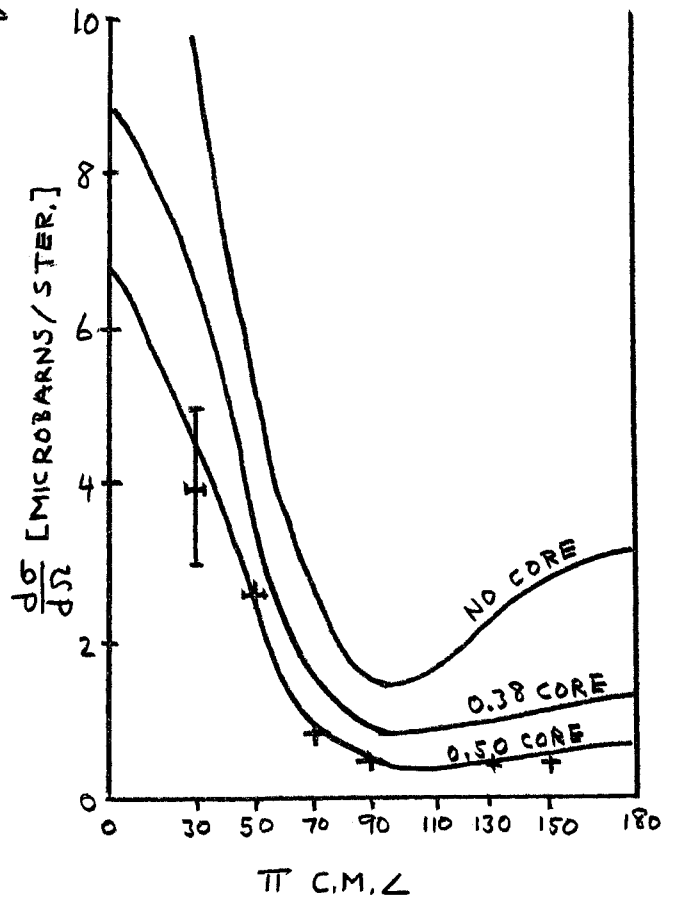


Fig. 23

The session closed with a report from Thorndike on cloud chamber observations of pion production from n-p collisions at the Cosmotron. The work was done by Shutt, W.B. Fowler, Whittemore, and Thorndike. They used a diffusion cloud chamber filled to 20 atm  $H_2$ , operating at 10,500 gauss. The neutrons were taken at zero degrees from the target, and the energy range was believed to be 1.0 to 2.2 Bev. The production of 5 or 6 pions was energetically possible. Events can be classified in terms of the number of observable prongs, as follows:

event	no.	event	no.	event	no.
PN	1	PP-0	3	PP-00	3
		PNOO	1	PP--+	5
PP-	3	PN+-	3	PNOOO	1
PNO	1	NN+0	1	PN+-0	3
NN+	1			NN+OO	1
				NN++-	3

The symbols +, 0, and - in this table refer to positive, neutral and negative pions. No five-prong events were seen, and this fact was taken to mean that triple-meson production was rare. The study was then limited to events with

three prongs, assuming no triple-meson events; the cases being observed were then presumably PP-, PP-0, and PN+- . In the event PP-, momentum balance requires that the sum of the transverse momenta be zero; this criterion was used to distinguish single from double production. It was also possible to identify mesons by specific ionization and curvature, or by virtue of the fact that it is kinematically impossible for protons to be emitted at angles greater than about  $75^\circ$  (lab). It was also possible to deduce the incident neutron energy for specific events; it was from this that the energy interval quoted above was obtained. About as many PP-events were found in the lower half of the energy interval as in the upper half. Out of a total of 157 three-prong events, 149 were classified as follows:

<u>type</u>	<u>certain &amp; probable</u>	<u>adjusted</u>	<u>theory</u>	<u>corrected</u>
PP-	18	24	15.7	19.3
PP-0	5	30	5.3	3.3
PN+-	86	95	13.8	8.4

It seems clear that the double production is considerably larger than the single. In this tabulation the "adjusted" numbers represent an attempt to fit as many events as possible into one of the three categories. The entries under "theory" are calculated from the Fermi statistical theory, given as percentage of all events; the "corrected" theoretical values, taking into account a factor  $1/n!$  are in even poorer agreement with the observations. Fermi commented, however, that the failure to find five-prong events certainly indicates that the interaction does not favor high multiplicity, and so prevents one from concluding that present theory must be essentially wrong. Oppenheimer noted that no current theory could give independence of multiplicity over this energy region, but Thorndike pointed out that the "independence" was by no means as well established as the large frequency of PN+-; the energy determinations are indirect and "somewhat subjective". H. Anderson asked whether or not events classified as PN+- might not have included some that were actually D+- . Thorndike replied that the latter process does occur: 4 cases were observed in which momentum balance was obtained under the assumption of a deuteron. But the confusion that is probably more likely than the one suggested by Anderson is the inclusion of some of these events in the category PP-, since transverse momentum is zero in both cases. A correction of this type would make double-meson production predominate even more strongly. W.D. Walker noted that there seemed to be a large difference between n-p and  $\pi^-$ -p at 1.5 Bev. From the plate work at Rochester it seemed that the most common process that occurred in  $\pi^-$ -p collisions was the production of one additional

meson. There is actually more energy available in the C.M. system for particle production for 1.5 Bev.  $\pi^+$ 's colliding with nucleons than for 1.8 Bev. nucleons colliding with nucleons.

(Dr. Thorndike has supplied us with supplementary data on the angle and momentum dependences observed in the above work. In the PP-events, the angular distributions given in number of observations per unit solid angle in center-of-mass were

	<u>0°-60°</u>	<u>60°-120°</u>	<u>120°-180°</u>
p	17	16	24
$\pi^-$	14	7	8

Data in the PP-0 events are not definite enough to give significant distributions. In the PN+- events the distributions were

	<u>0°-60°</u>	<u>60°-120°</u>	<u>120°-180°</u>
p	30	25	78
n	66	27	42
$\pi^+$	44	34	70
$\pi^-$	66	39	36

Momentum distributions, given as number of observations at all angles, were

	<u>0-0.2</u>	<u>0.2-0.4</u>	<u>0.4-0.6</u>	<u>0.6-0.8</u>	<u>med.</u>	<u>med K.E.</u>
PP- $\pi^-$	4	17	7	1	.33	.22
PN+- p	2	27	30	9	.43	.12
n	6	28	30	17	.43	.12
$\pi^+$	34	30	6	0	.205	.11
$\pi^-$	34	37	5	0	.215	.12

The angular correlations between pairs of product particles in PN+- events, given as number of observations per unit solid angle vs. angle between particles were

	<u>0°-60°</u>	<u>60°-120°</u>	<u>120°-180°</u>
p-n	4 $\pm$ 3	9 $\pm$ 3	120 $\pm$ 16
p- $\pi^-$	20 $\pm$ 7	47 $\pm$ 7	56 $\pm$ 11
p- $\pi^+$	18 $\pm$ 6	33 $\pm$ 6	86 $\pm$ 13
$\pi^-$ - $\pi^+$	28 $\pm$ 8	39 $\pm$ 6	74 $\pm$ 12

All of these data are consistent with the statement that protons and positive pions are emitted preferentially backward in the center of mass system. EMH)

#### THEORETICAL SESSION

Monday afternoon, Professor G. Wentzel presiding.

Goldberger presented the following work, carried out in collaboration with S. Deser and W. Thirring.