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HIGH ENERGY NUCLEON-NUCLEON SCATTERING EXPERIMENTS AT BERKELEY

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Publication Date

1950-08-03

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HIGH ENERGY NUCLEON-NUCLEON SCATTERING EXPERIMENTS AT BERKELEY

Geoffrey F. Chew and Burton J. Moyer

August 3, 1950

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HIGH ENERGY NUCLEON-NUCLEON SCATTERING EXPERIMENTS AT BERKELEY*

Geoffrey F. Chew and Burton J. Moyer

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August 3, 1950

One of the ways to study the forces which hold a nucleus together is by means of experiments in which two free nucleons (neutrons or protons) are caused to collide. Nuclei are composed of neutrons and protons bound to each other, and the forces acting between them in the bound state will produce a scattering when they collide as free particles. This principle was first used by Rutherford to investigate with alpha-particle projectiles the outer regions of the force field of a nucleus, which turned out to be purely Coulomb and repulsive. Rutherford's success caused nuclear physicists to hope that the fundamental laws underlying the short range characteristically nuclear forces might also be revealed by scattering experiments. This hope tended to be borne out by early work which showed that nuclear forces are attractive and confined to distances of the order of 10^{-13}cm. Just because of this short range, however, it was impossible until a few years ago to get more detailed information, because there existed no accelerators capable of producing nucleons with energies greater than about 15 Mev. A nucleon of this energy or less has a wavelength longer than the overall extension of the nuclear force so that it can not be used to study details of the latter. The construction of new accelerators at Berkeley[1] in the University of California Radiation

$\lambda_{15} = 1.13(10)^{-13}$

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* G. F. Chew, B. J. Moyer, Am. Journ. Phys. 18, 125-35 (1950)(UCRL-444)
G. F. Chew, B. J. Moyer, to be published (UCRL-663)

Laboratory, however, made available neutron energies up to 280 Mev and proton energies up to 350 Mev, with correspondingly shorter wave-lengths. For this reason, neutron-proton and proton-proton scattering experiments were high on the priority list of the Berkeley research program.

When the Berkeley experiments were begun, there was hope that many features of simplicity would be found, tying together the known properties of nuclei with the conjecture that mesons are responsible for nuclear forces[2]. The results so far obtained have not weakened the position of the meson hypothesis; indeed they have given it qualitative confirmation. However the results are certainly not "simple", and it now seems doubtful that they can be used, by themselves, to deduce the complete picture. They remain, of course, as facts which any future theory, meson or other, must explain. In this paper the various high energy scattering experiments will be described, and the interpretation given by the Berkeley theoretical group discussed.

I Neutron-Proton Scattering.

It is not really permissible to use non-relativistic mechanics to describe neutron-proton scattering at energies of the order of 100 Mev. The velocity of a 100 Mev neutron is nearly half that of light, so that effects of retardation and of mass increase are not negligible. It is expected, however, that great qualitative errors will not arise from using the non-relativistic approximation. For descriptive purposes here, this will suffice although in the actual analysis of the experiments an attempt was made to include at least some of the relativistic effects.

The energy-momentum conditions for a non-relativistic neutron-proton collision are simple because of the near equality of the two masses and can be summarized quite concisely. If the proton is initially at rest and the neutron has a momentum P_o, then the final trajectories of neutron and proton are at right angles and the momentum of either is $P_o \cos \phi$, where ϕ is the angle of emission of that particle. (See Figure 1.) For definiteness we shall henceforth use the symbol ϕ to refer to the final proton angle since that is the one observed in the Berkeley experiments. The symbol, θ, will be used to denote the final neutron angle in the center of mass coordinate system (the system in which neutron and proton approach each other with equal and opposite velocities). It is not hard to show that $\theta = \pi - 2\phi$.

The reason protons are bombarded with neutrons instead of vice-versa is, of course, that a target of free neutrons cannot be made. The neutron beams which can be obtained from the 184 inch cyclotron are not monoenergetic, as discussed in the previous article on high energy reactions[3], but this need not be a serious difficulty, since the final momentum of the proton is a measure of the incident neutron energy. A satisfactory experiment, however, requires a knowledge of both the energy and the angle of the recoil protons.

A. Proportional Counter Measurements with 90 and 40 Mev Neutrons[4]

One method of measuring the energy and angle of the recoil protons is by means of a proportional counter telescope, with supplementary absorbers. The general arrangement of the apparatus which was used for this measurement is shown in Figure 2. The neutron beam entered from the left and knocked out protons from the scattering target. A telescope of three proportional counters pointing at the scatterer served to define the angle of the recoil protons. Interposed between the last two counters was a copper absorber (A in Figure 2) of a thickness in the case of 90 Mev neutrons such that it would stop protons of an energy less than 66 $\cos^2 \phi$ Mev. This means that all neutrons of an energy less than 66 Mev in the incident beam were ignored when only triple coincidences were recorded. Some protons were lost, also, from scattering in the absorber, but this effect could be corrected for.

To obtain a sufficient concentration of protons in the scatterer, it was necessary to use an hydrogenous compound rather than pure hydrogen. The choice made was polyethylene, which has the chemical composition, $(CH_2)_n$. By alternating this target with another of pure carbon having the same stopping power, and taking differences, it was possible to deduce the scattering due to the hydrogen alone. This is not quite as satisfactory as a direct measurement, and the experiment may eventually be done with a liquid hydrogen target.

The information given by the experiment described was the relative angular distribution for the scattering of neutrons whose energy was at least 66 Mev and on the average was 90 Mev. The results are summarized by the lower curve in Figure 3. The abscissa of this diagram is $\theta = \pi - 2\phi$, the final neutron angle in the center of mass system. [At energies below 15 Mev the angular distribution in this coordinate system is flat as discussed below.] The upper curve of Figure 3 is the scattered distribution for neutrons of average energy 40 Mev (produced by stripping of 80 Mev deuterons). The various symbols refer to different runs, while the stars give the final best available average. Neither curve extends to 0° because the proton recoils for such small angles have too small an energy to be detected.

The absolute normalization of the curves in Figure 3 had to be obtained from an independent determination of the total cross section.

This was carried out by a conventional attenuation measurement of the neutron beam in good geometry. This simply means that a neutron flux was measured before and after passing through a hydrocarbon absorber and also a graphite absorber containing the same amount of carbon. The detector subtended a sufficiently small angle so that a negligible number of scattered neutrons were included. From the differences of the three measurements the total cross section of the hydrogen could be deduced. The average values of the total cross section, used in the normalization of Figure 3 were 0.076×10^{-24} cm^2 for 90 Mev and 0.170×10^{-24} cm^2 for 40 Mev. An extrapolation of the curves to zero angle had to be guessed, but because of the small solid angle of the unknown region this did not introduce much uncertainty. More recent unpublished measurements by Leith and Hildebrand indicate that the 40 Mev total cross section may be as high as 0.201×10^{-24} cm^2.

B. Cloud Chamber Measurements with 90 Mev Neutrons[5]

To make sure that no large systematic errors were being made in the counter experiments, a completely independent determination of the 90 Mev n-p angular distribution was carried out with a hydrogen filled Wilson cloud chamber, placed in a strong magnetic field. The direction and curvature of the proton tracks observed after passing a burst of neutrons through the chamber gave all the required information.

The cloud chamber (Figure 4) was 16 inches in diameter, with a useful illuminated depth of 3½ inches, and the neutrons entered through a 5-mil aluminum window in the wall of the cylinder. The chamber was filled with hydrogen at a pressure of 110 cm of Hg and saturated with an alcohol-water mixture. A pair of Helmholtz coils supplied the magnetic field of 14,000 gauss, which was pulsed on for 0.15 seconds every two minutes. During this interval the cloud chamber was expanded and the cyclotron pulsed near the end of the sensitive time of the chamber. Great care was taken to minimize turbulence, the traditional bugaboo of cloud chamber measurements, and extremely sharp tracks were produced. Figure 5 gives an example. Photographs were taken with a stereocamera and reprojected on a translucent screen. The curvature and direction of all proton tracks, making an angle of less than 84° with the incident neutron beam, were accurately measured. This limit was chosen because at larger angles the tracks are so short that they may sometimes be overlooked.

The momentum of each proton could be deduced from its radius of curvature in the known magnetic field, and consequently the energy of the neutron producing the recoil was known. (Figure 1). This gave an independent determination of the stripping neutron spectrum, which checked well with previous data. 1764 knock-on protons were counted, excluding those produced by neutrons of less than 40 Mev. Since there were relatively few neutrons between 40 and 66 Mev, this constituted a measurement of essentially the same quantity as in the counter experiment. The data are compiled in the histogram of Figure 6.

It is seen that the statistical accuracy is not as high as in the measurement with proportional counters, but that the overall agreement with the latter is good. This fact gives one much more confidence in the counter results, since many unfamiliar phenomena were encountered in this first precision measurement of a high energy scattering cross section.

C. Discussion of N-P Measurements

In the introduction it was pointed out that when the de Broglie wave-length is longer than the range of the nuclear force one can derive no information about the details of the latter. This fact manifests itself experimentally in an angular distribution which is spherically symmetric in the center of mass system. In other words, low energy measurements of the distribution shown in Figures 3 and 6 have always yielded a flat function, showing that only the S part of the incident wave was being scattered. The anisotropy of the Berkeley results was the first indication of a nuclear interaction in states of non-zero angular momentum.

A detailed phenomenological analysis of the high energy n-p experiments has been made by R. S. Christian and E. Hart of the Radiation Laboratory[6]. Their most important conclusion was that the interaction in p states (one unit of orbital angular momentum) of the proton-neutron system is almost absent, most of the observed angular dependence being due to d states (two units). This fact is suggested at once by the near symmetry of the angular distribution about 90°, and it is further borne out by the low total cross section. The result was quite unexpected on the basis of existing ideas about the saturation property of nuclear forces[2] and is far from being understood at the present time.

A more naive interpretation of the results, suggested by meson theory, is to say that the strong maximum at 180° shows the existence of an exchange force. In other words, one obvious mechanism by which a neutron could be found with such a high probability in the backward direction is for the incident particles to have exchanged roles in the process of scattering, the proton becoming a neutron and vice-versa. This is probably the case, qualitatively, but the existence of a second peak at 0° shows that ordinary forces are not absent. No reasonable meson theory yet put forward can quantitatively explain the entire angular distribution.

A measurement of the n-p cross section at a still higher energy has also been made at Berkeley[7]. "Knock-out" neutrons, produced by the 350 Mev proton beam impinging on a beryllium target[3], were used. This measurement, for many reasons, is not so precise as the one already described. The results are qualitatively similar, however, the p scattering still being absent. The central valley of the angular distribution is deeper and the forward peak narrower, but this is to be expected from the higher energy.

II Proton-Proton Scattering.

The kinematics of proton-proton scattering are the same as for neutron-proton scattering because again one is dealing with two particles of the same mass. Experimentally, however, there is no way to decide whether the proton observed at a particular angle after the collision is the incident particle or the recoil. The principles of quantum mechanics, indeed, do not allow such a question to be asked and require that the wave function which describes the scattering be antisymmetric in the coordinates of the two protons. The quantity to be measured and to be interpreted is simply the number of protons at a particular angle. The distribution of this number must obviously be symmetric about 90° in the center of mass coordinate system, and its integral over all angles is two per collision. The symmetry is always used in a careful experiment as a check on the results.

In addition to this difference between n-p and p-p scattering, which is due to the identity of the two protons, there is the Coulomb repulsion which was absent in the n-p case. This produces strong effects at low energies and relatively smaller effects as the energy increases. It is well understood at all energies, however, and can be effectively eliminated in the theoretical analysis, reducing the problem to that of two uncharged protons. Thus it is a sensible procedure to compare the purely nuclear forces acting in the n-p and p-p systems respectively, even though the results of the corresponding scattering experiments may look quite different. One of the features of simplicity in the nuclear force picture which had been suggested by low energy results was that the n-p and p-p forces were the same. This, as we shall see, turns out to be far from true.

A. Counter Measurements with Protons from the Linear Accelerator

As described in the first article of this series, the Berkeley linear accelerator is capable of producing an intense, well collimated, almost monoenergetic beam of protons; and a supplementary steering magnet can be used to define the energy as accurately as is desired. This allowed the measurement of proton-proton scattering near 30 Mev to be more precise than the aforementioned neutron-proton experiments. Because of the importance of this measurement, it was undertaken by two separate groups, using entirely different methods. One group employed counters in an essentially conventional scheme[8]. This method will be described first.

The experimental set-up is outlined in Figure 7. The proton beam, collimated to a diameter of 7 mm., entered the apparatus from the left through a nylon window. The entire apparatus was filled with hydrogen gas at atmospheric pressure, although the cylindrical region from which scattering was accepted was only two centimeters long by half a centimeter in diameter. The absolute intensity of the proton current was measured by collecting the charge in a Faraday cup and seven proportional counters shaped as annular rings recorded the scattering at seven different angles. Only the range 15° - 51° in the laboratory system was covered, because of mechanical difficulties in the construction of the apparatus. This meant that the intensity at only one position was checked against the complementary angle intensity.

Background, due to energetic neutrons which produced recoils in the counters, was a problem. These neutrons were generated at a variety of places by the primary proton beam and were greatly reduced by a careful arrangement of absorbers. The remainder, which accounted for less than 10 percent of the counting rate were dealt with by the familiar subtraction procedure. This simply meant making alternate runs with and without hydrogen in the apparatus and taking the difference.

The results of the counter measurement are given as the triangles in Figure 8, plotted in the conventional way against the angle in the center of mass coordinate system. Only the range 0 - 90° is shown because of the symmetry about 90°. The results will be discussed in II - D.

B. Photographic Plate Measurements with Protons from the Linear Accelerator

A completely independent measurement of the 30 Mev p-p cross section has also been made, using a photographic method of detection[9]. A number of plates were set like fins, edge-on to a small cylindrical volume which was filled with hydrogen. The proton beam from the linear accelerator was allowed to pass through this volume and some of the scattered protons found their way into the emulsion, producing tracks which could be examined under a microscope. The angle which these tracks made with the edge of the plate was the same as the angle of scattering.

Figure 9 shows the chief features of this arrangement. After passage through the magnetic field to improve the definition of the energy the proton beam was collimated by a succession of three slits, so that it entered the scattering chamber with a width of only 1/16 of an inch.

The near edge of each photographic plate was half an inch from the center of the beam, a picture of the plate holder being shown in Figure 10.

The chief difficulty with this method arose from slit scattering. Protons may strike the edges of the collimating slits and be deflected enough to get into the emulsion. This circumstance made it impossible to get reliable data at angles less than 10°. Protons observed entering the plates at large angles, of course, must have originated in the hydrogen gas. The maximum observable angle was set by the same consideration as in the n-p experiments: Protons at angles greater than 80° have such a small range that their tracks could not be reliably counted.

This experiment, then, gave the angular distribution of protons between 10° and 80° in the laboratory system, a considerable improvement over the range covered by the counter experiment, since the intensity at every angle was checked by the intensity at the complementary angle. Statistically, of course, the counter method had the advantage, being able to record up to five protons per second per counter. A single person is only able to count between 250 and 400 tracks a day in a photographic emulsion; so that 30 man days are required to accumulate 10,000 counts, the order of magnitude needed for a good measurement of this kind.

Dividing the entire range of angles into 8° intervals, an angular distribution was constructed from the 11,000 recorded tracks. Smaller intervals could just as well be chosen, but then the vertical accuracy of each point would suffer. Since the curve is not expected to have sharp features at this energy, a rather small number of intervals each with a good statistical accuracy seemed the most sensible choice. The results are shown as the squares in Figure 8. The agreement between the two independent experiments is seen to be good.

C. Counter Measurements with 350 Mev Protons from the Synchrocyclotron

The proton-proton scattering cross section at 350 Mev has also been measured, using the proton beam from the 184 inch synchrocyclotron[10]. Once again two different techniques were employed, but both were based on counters. The first technique was almost identical with that described in section I-A for n-p scattering. The same counter telescope, indeed, was used in the two experiments. The second technique again used three counters but in a different arrangement. Two were used without any absorber to form a defining telescope. The third was set at an angle of 90° (actually 85.5° because of relativistic corrections) with respect to this telescope and coincidences between the two positions were required. Coincidences were caused by the two protons emerging from a p-p collision, since they necessarily occur at right angles to each other. Chance simultaneous trippings of the two counters by background radiation were infrequent enough to be ignored. The results of the two measurements were in agreement and extremely surprising. In the center of mass coordinate system of the two protons, the scattering cross section was found to be a constant over all the angles measured (40°-90°), with a magnitude of $5 \times 10^{-27}\text{cm}^2$ per unit solid angle.

D. Discussion of P-P Measurements

Almost anything different from the very flat p-p angular distributions observed at 32 and at 350 Mev would have been more understandable. The proton wave-length is sufficiently short already at 32 Mev to make interaction in p and d states possible, but as Figures 7 and 8 show, no such interactions manifest themselves in an obvious way. The weak angular dependence observed is easily attributable to the Coulomb field. In spite of a similar looking result at 350 Mev, however, one can be quite sure that scattering does occur there in states of non-zero angular momentum, because the magnitude of the cross section is too great to be due to s scattering only. A rather complicated force scheme for the states of odd orbital angular momentum must be invoked to explain the high flat angular distributions observed at both energies.

The theoretical analysis of the foregoing data, as carried out at Berkeley[11] cannot be described here, but the conclusions may be stated as follows: (1) The p-p force is not the same as the n-p, there being a strong interaction in states of odd orbital angular momentum (p, f, . . . states) in the former case and only weak if any in the latter. (2) In odd states, the p-p forces do not act along the line joining the particles but are correlated with the spatial orientation of the combined spin of the two protons. These conclusions were reached on the basis of a phenomenological picture of nuclear forces, in which they are derived from non-velocity dependent potentials. The general conclusions have a good chance of standing up even if the potential model is wrong, but they should not yet be regarded as unequivocal.

That non-spherical terms occur in the nuclear force scheme has been known since the discovery of the quadrupole moment of the deuteron. The p-p results, however, if the interpretation is correct, constitute the first strong manifestation of the asymmetry in scattering phenomena. There is no tie-in with the deuteron, however, because there the effect is in states of even orbital angular momentum while in proton-proton scattering the effect occurs in odd states.

The lack of similarity between n-p and p-p interactions necessitates no fundamental change in the idea that mesons are responsible for nuclear forces but it upsets a pleasant feature of simplicity which had almost been accepted among nuclear physicists.

Conclusion

It is possible that this is an inappropriate time to discuss the Berkeley experiments, since at the moment the results are so poorly understood. A theory may perhaps be proposed very soon to clarify the situation, but the probability of this seems small. The most widely shared opinion about nuclear forces at present is that they are due to the exchange of mesons between nucleons but that so many mesons are involved, at least in situations so far considered experimentally, that the overall effect is complicated and cannot be used as the starting point in making a theory. Attention is now turning to the mesons themselves in the hope that they will behave more simply than the nucleons which they so profoundly influence. The final paper in this series will give an account of the preliminary experiments at Berkeley which have the objective of determining the properties of mesons.

The work described in this paper was performed under the auspices of the Atomic Energy Commission.

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FIGURE CAPTIONS

Figure 1. The momentum relations in a non-relativistic neutron-proton collision.

Figure 2. Arrangement of target and counter telescope for measuring the angular distribution of protons knocked on by high energy neutrons.

Figure 3. Angular distribution in the center of mass system for neutrons of energy 40 and 90 Mev scattered by protons.

Figure 4. Diagram of cloud chamber used for 90 Mev n-p scattering experiment.

Figure 5. Example of cloud chamber photograph obtained in the measurement of 90 Mev n-p scattering. Only proton tracks originating in the gas are significant.

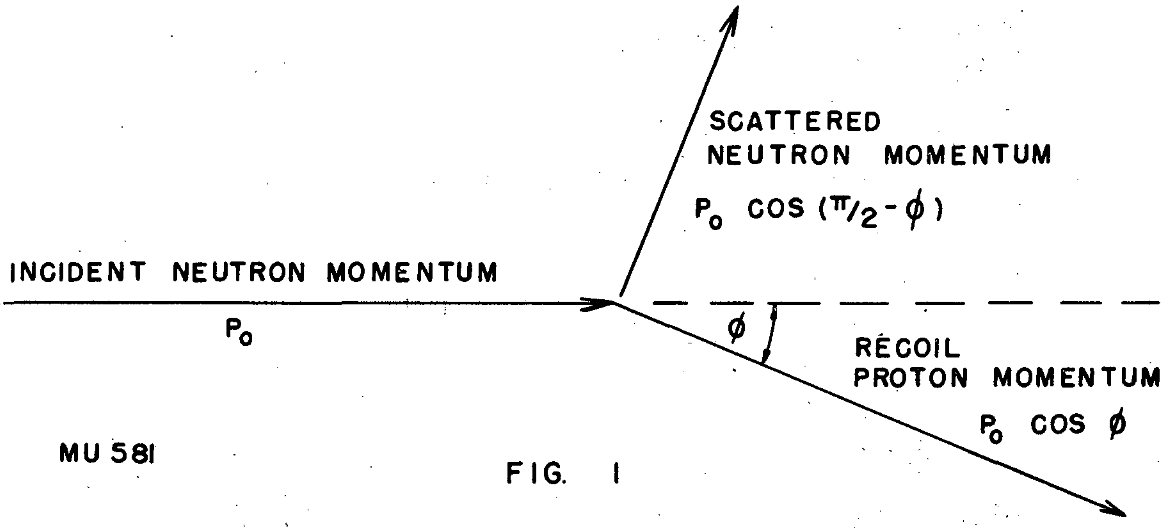
Figure 6. Histogram compilation of data from cloud chamber experiment.

Figure 7. Scattering chamber and surrounding counters for measurement of 32 Mev proton-proton scattering.

Figure 8. Results of two independent measurements of p-p scattering near 30 Mev. The slight difference in energy accounts for the different absolute values. The solid and dotted curves are theoretical, showing what is to be expected if nuclear interaction occurs in the S or in both S and d states, respectively.

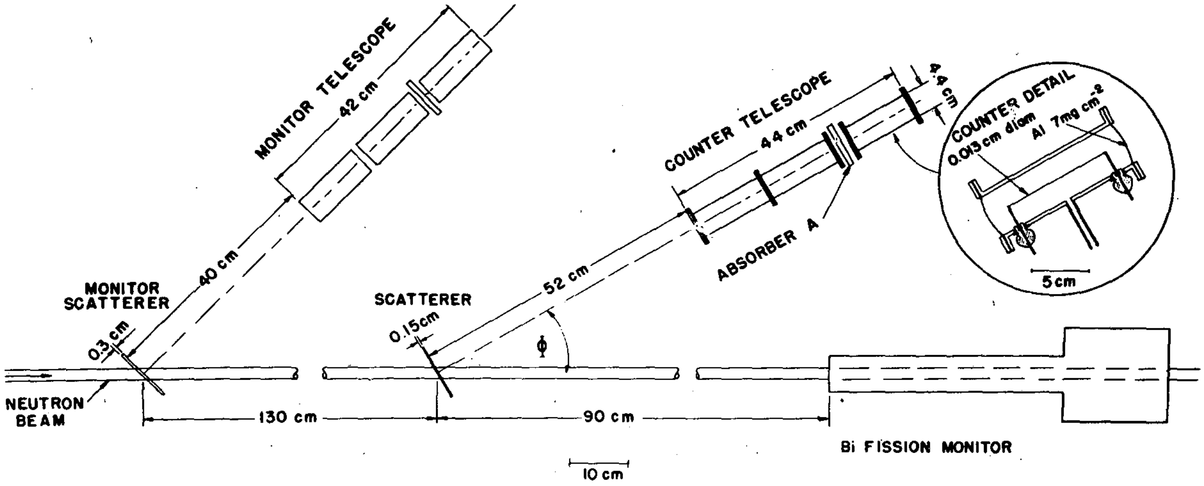
Figure 9. Diagram of scattering chamber for photographic measurement of p-p scattering at 29.4 Mev.

Figure 10. Photograph of holder for photographic plates used in 29.4 Mev p-p scattering experiment at Berkeley.


SCATTERED
NEUTRON MOMENTUM
$P_0 \cos(\pi/2 - \phi)$
INCIDENT NEUTRON MOMENTUM
P_0
ϕ
RECOIL
PROTON MOMENTUM
$P_0 \cos \phi$

MU 581

FIG. 1


MONITOR TELESCOPE
42 cm
40 cm
MONITOR SCATTERER
0.3 cm
NEUTRON BEAM
130 cm
SCATTERER
0.15cm
52 cm
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90 cm
COUNTER TELESCOPE
44 cm
4.4 cm
ABSORBER A
COUNTER DETAIL
0.013 cm diam
Al 7mg cm^{-2}
5 cm
Bi FISSION MONITOR
10 cm

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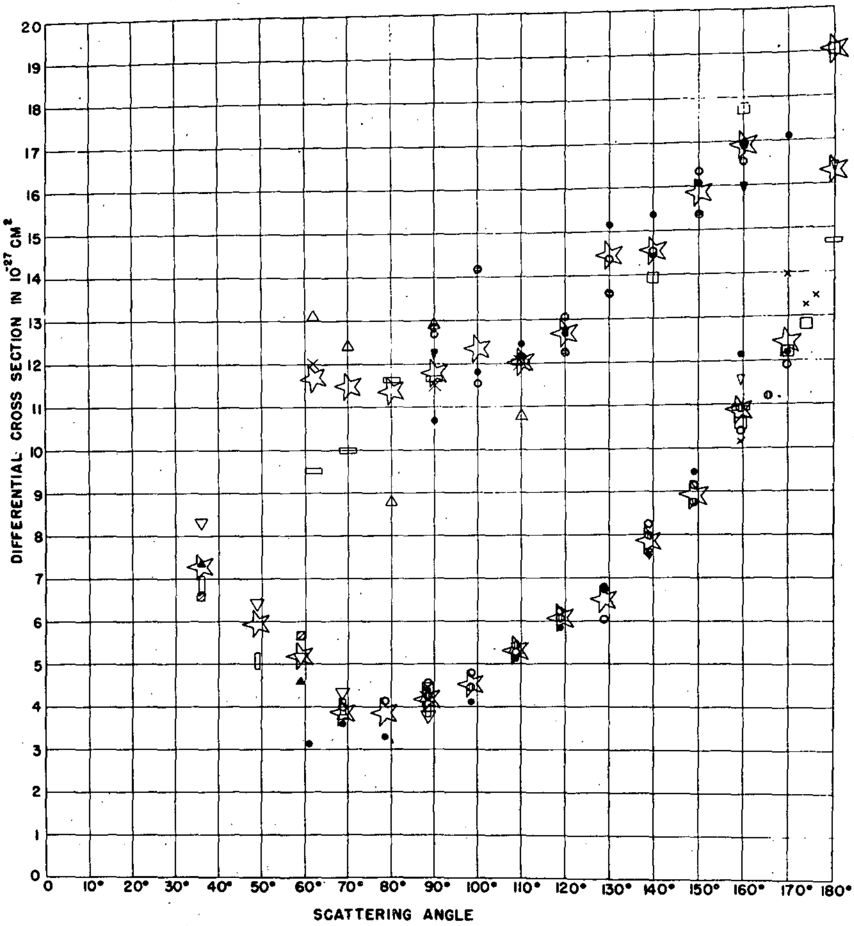
FIG. 2


DIFFERENTIAL CROSS SECTION IN 10^{-27} CM^2
0
1
2
3
4
5
6
7
8
9
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11
12
13
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10°
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30°
40°
50°
60°
70°
80°
90°
100°
110°
120°
130°
140°
150°
160°
170°
180°
SCATTERING ANGLE

FIG. 3

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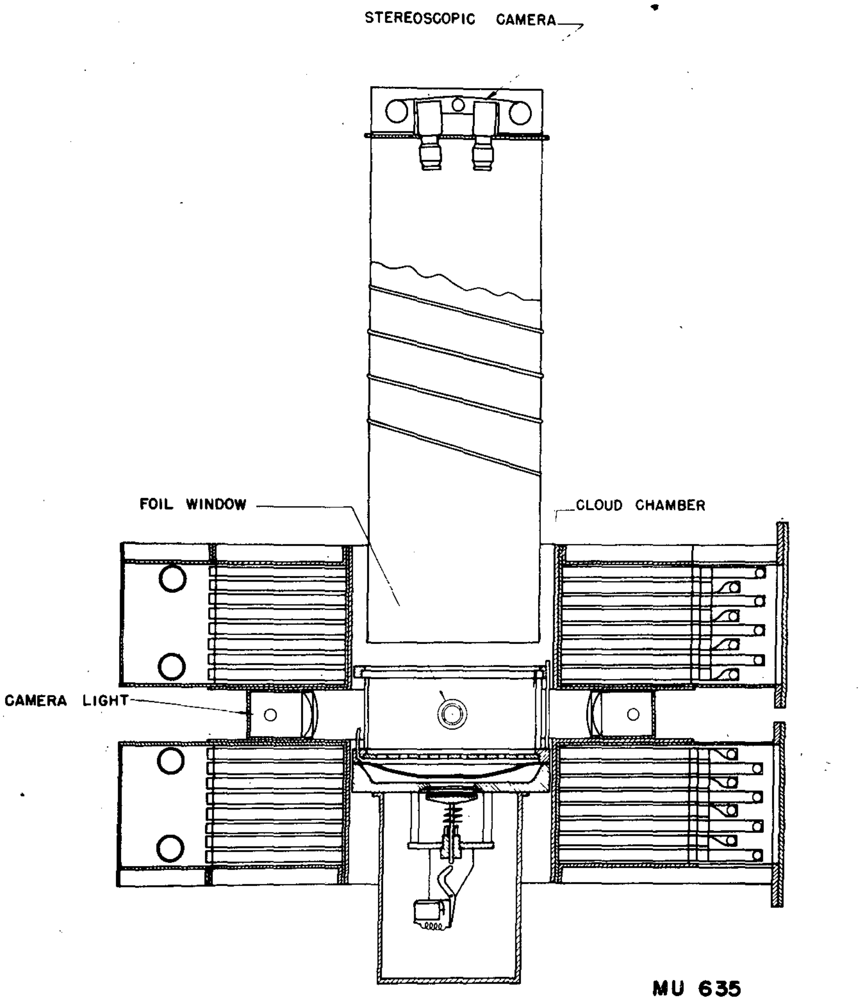


FIG. 4

15- INCH HELMHOLTZ-COIL CLOUD CHAMBER

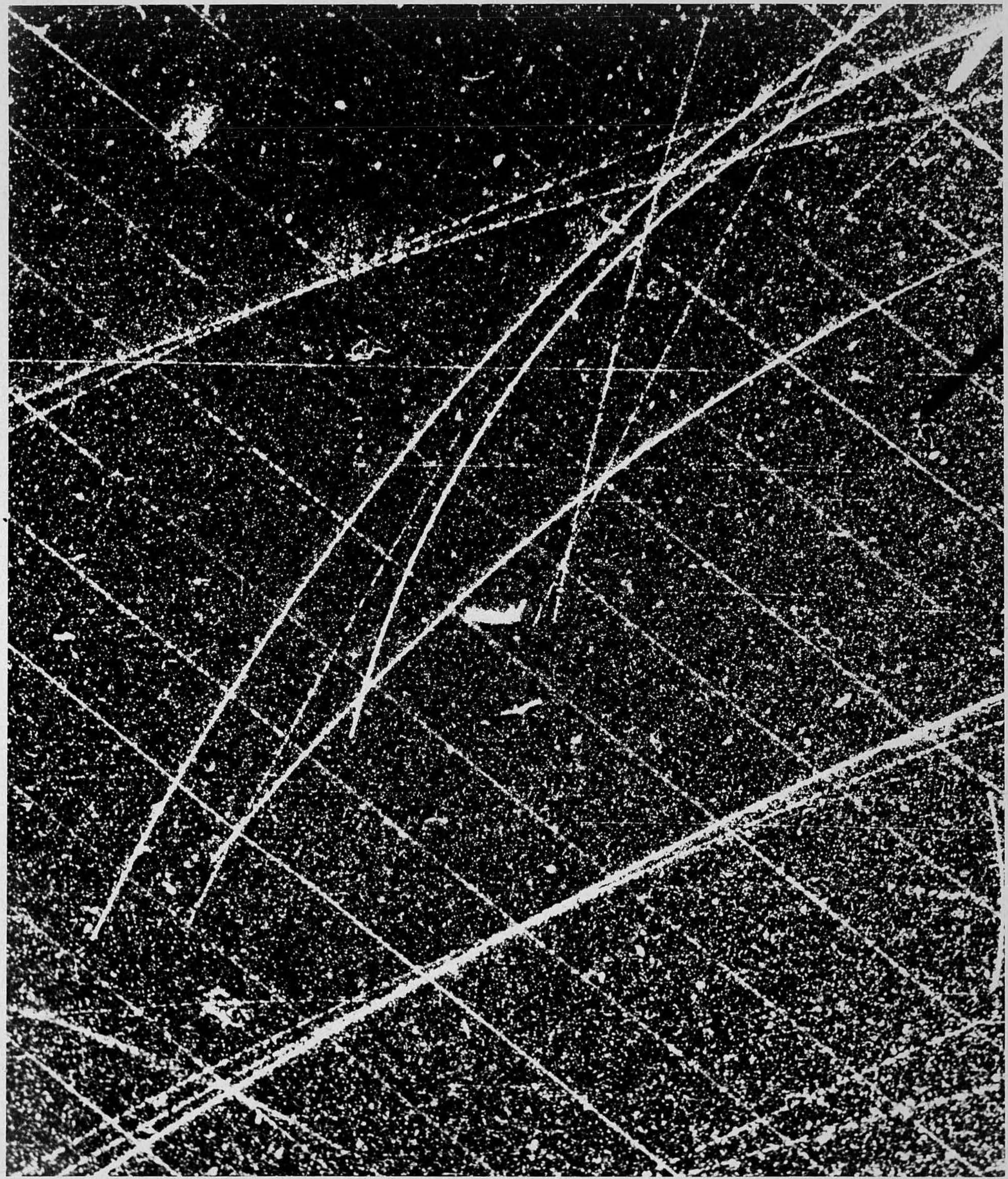


FIG. 5

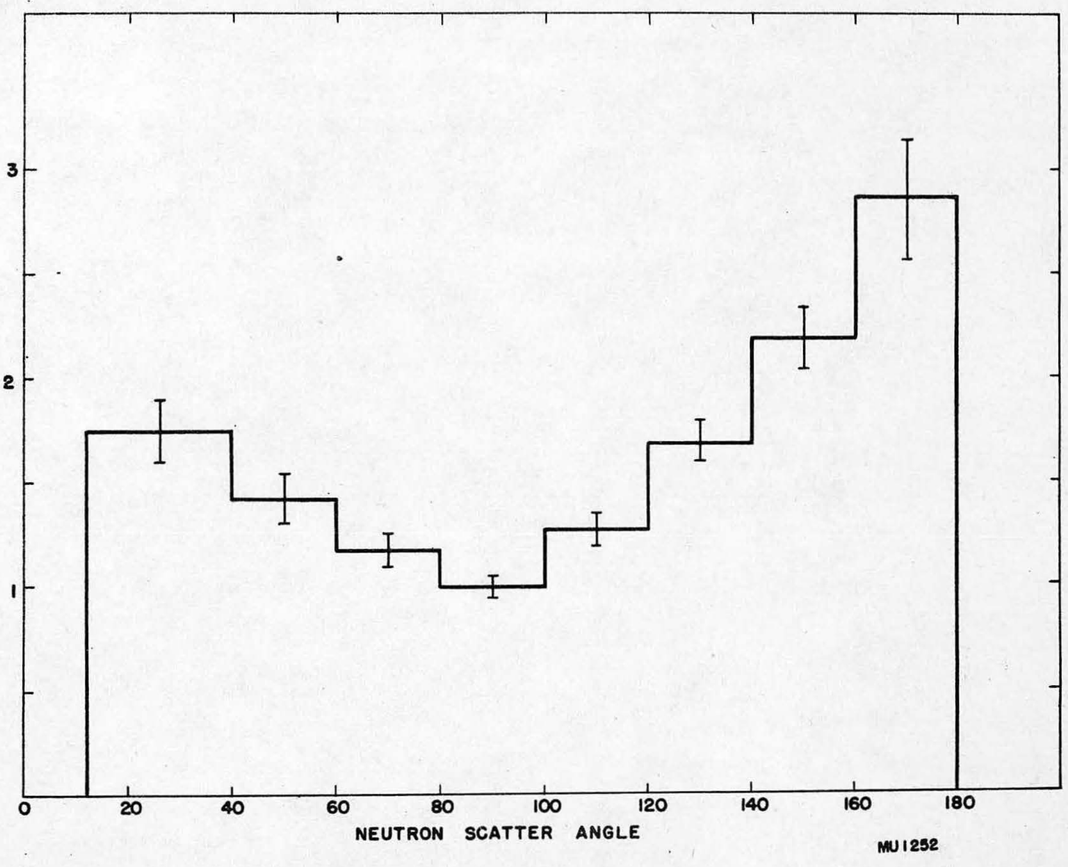

3
2
1
0
20
40
60
80
100
120
140
160
180
NEUTRON SCATTER ANGLE
MU1252

Fig. 6

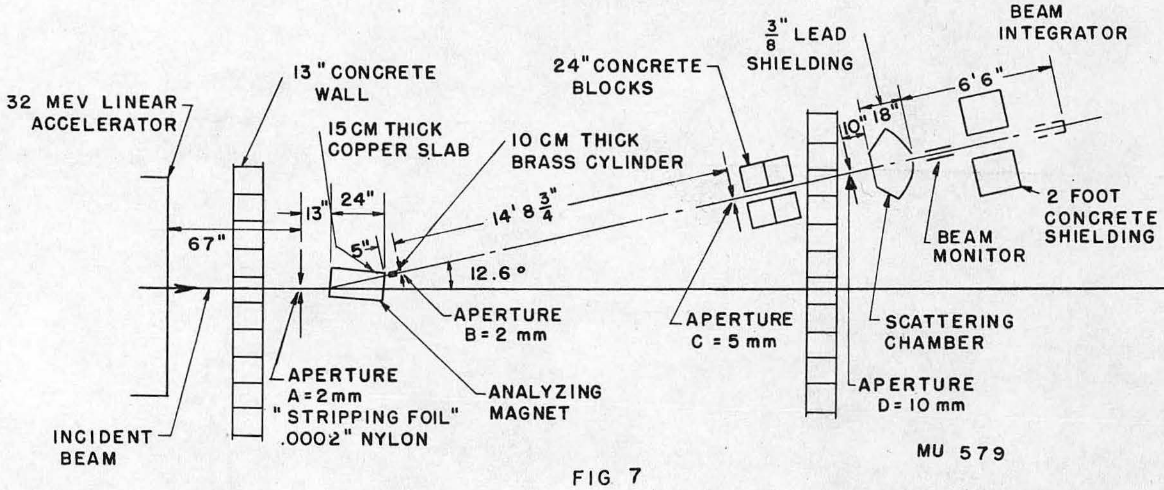
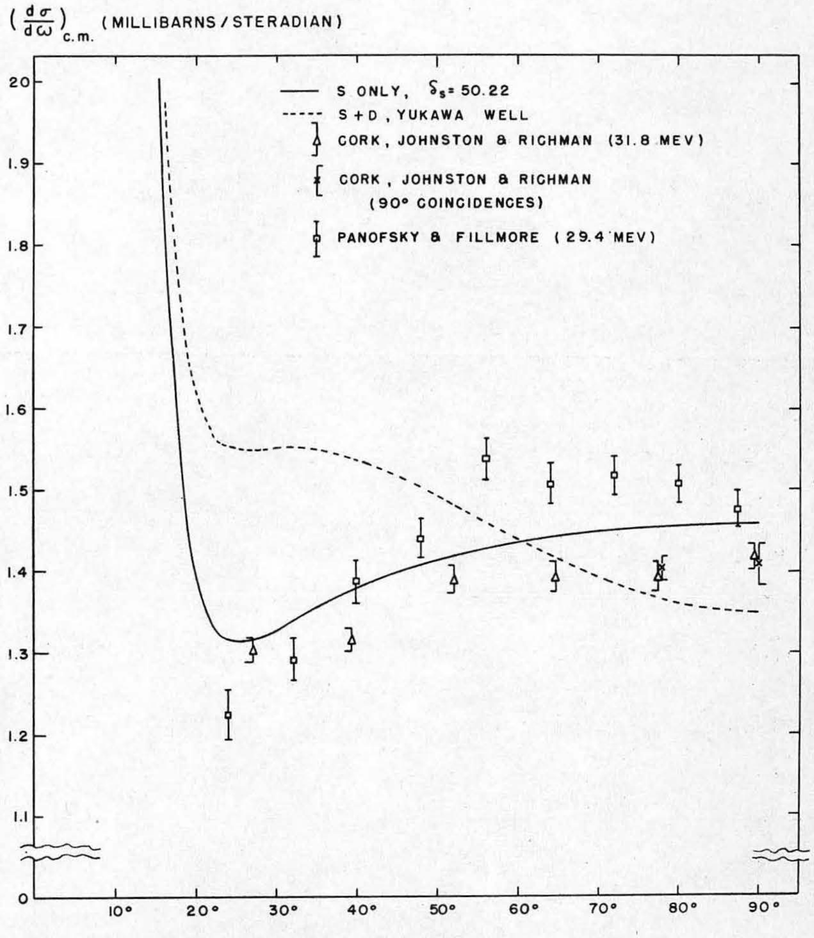

32 MEV LINEAR ACCELERATOR
13" CONCRETE WALL
15 CM THICK COPPER SLAB
10 CM THICK BRASS CYLINDER
24" CONCRETE BLOCKS
$\frac{3}{8}$" LEAD SHIELDING
BEAM INTEGRATOR
6'6"
10"
18"
67"
13"
24"
5"
14' 8 $\frac{3}{4}$"
12.6°
2 FOOT CONCRETE SHIELDING
BEAM MONITOR
APERTURE B = 2 mm
APERTURE C = 5 mm
SCATTERING CHAMBER
APERTURE A = 2 mm "STRIPPING FOIL" .0002" NYLON
ANALYZING MAGNET
APERTURE D = 10 mm
INCIDENT BEAM
MU 579

FIG 7



(dσ/dω)c.m. (MILLIBARNS / STERADIAN)
S ONLY, δs = 50.22
S + D , YUKAWA WELL
CORK , JOHNSTON & RICHMAN (31.8 MEV)
CORK , JOHNSTON & RICHMAN (90° COINCIDENCES)
PANOFSKY & FILLMORE (29.4 MEV)
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
0
10°
20°
30°
40°
50°
60°
70°
80°
90°
θc.m. IN DEGREES

MU 580

FIG. 8

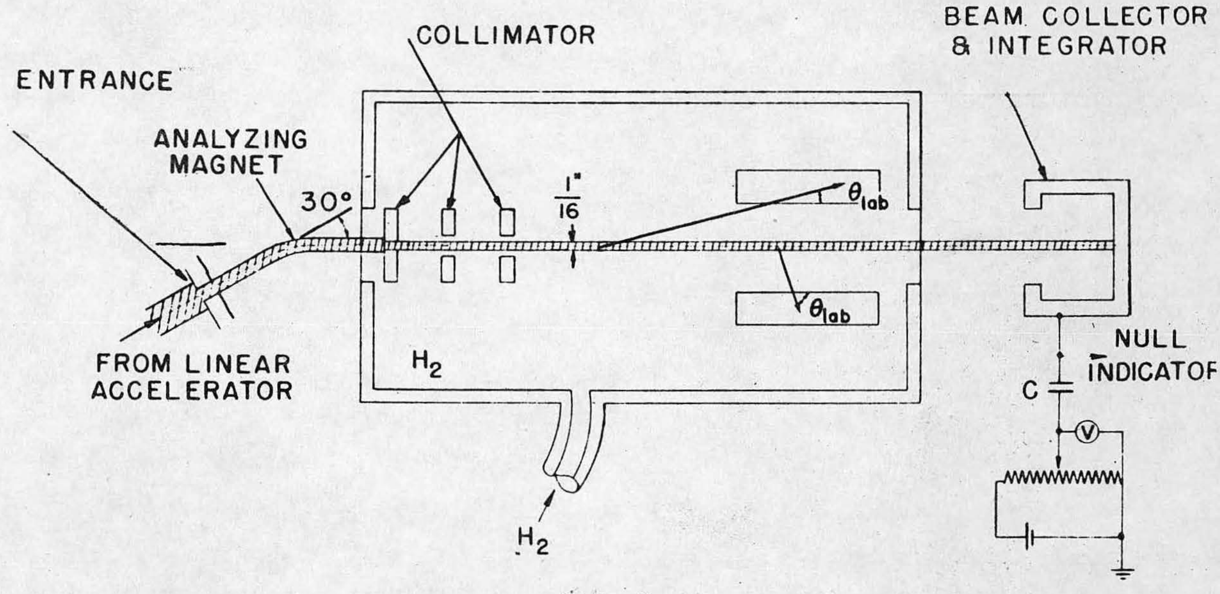

BEAM COLLECTOR & INTEGRATOR
COLLIMATOR
ENTRANCE
ANALYZING MAGNET
30°
1" / 16
θlab
θlab
FROM LINEAR ACCELERATOR
H2
H2
NULL INDICATOF
C
V

FIG. 9

MU 634

FIG 10

OZ-360