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NEUTRON-PROTON SCATTERING AT 90 MEV

Robert Hamlon Fox (Thesis)

August 14, 1950

Berkeley, California

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NEUTRON-PROTON SCATTERING AT 90 MEV

Robert Fox

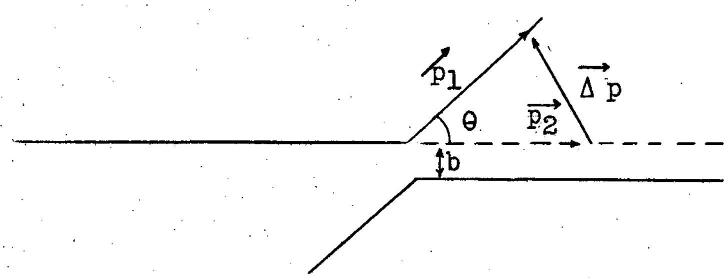
I. INTRODUCTION

In the last two decades many experiments have been carried out to obtain data on the neutron-proton interaction. Most of these have been in the low and medium energy range. In this energy range none of the experiments give information concerning the explicit radial dependence of the forces or of the forces in other than S states, and even the ranges are determined only approximately.[1] To obtain explicit information on the radial dependence of the forces experiments at high energy are required so that $\lambda\!\!\!^{-}$, the De Broglie wavelength of the incident particle in the c.g. system, is less than the range of the forces.

Therefore, when the 184-inch cyclotron first produced a beam of neutrons of 90 Mev mean energy by stripping of deuterons,[2] it was used by Segrè and co-workers[3] to do neutron-proton scattering experiments at 40 Mev and 90 Mev. In their experiments, both the total cross sections and the angular dependence of the differential cross sections at the two energies were studied.

It turns out[1] that these experiments, together with the low energy experiments are sufficient to rule out the symmetrical theory for central forces. Also, the inclusion of a tensor potential is required to give the right shape at 90°. This is in agreement with the existence of the quadrupole moment of the deuteron.

There is, however, one feature of the 90 Mev angular distribution which appears to warrant further investigation. This is the apparent existence of a high peak at 180° in the c.g. system. This peak represents a 30 percent increase in $d\sigma/d\Omega$ in going from 170° to 180°. That such a sharp peak represents a long tail of appreciable depth in the potential can be shown qualitatively by the following uncertainty principle argument: Consider a collision in the c.g. system between two particles of equal mass.



We can assign the collision parameter "b" to such a collision. Let $b_{max} = R$ where R is maximum separation at which the interaction is of appreciable strength (i.e. R represents the range of the interaction). Then, for those collisions with values of $b \sim R$ there will be a distribution in the momentum transfer and hence in the scattering angle. Now, by geometry and since $p_1 = p_2 = p$, $\Delta p = \left|\vec{p}_1 - \vec{p}_2\right| = \left[2p^2 (1-\cos\theta)\right]^{1/2} = 2p \sin\theta/2 \simeq p\,\theta$ for small angles. Now, one can replace b by Δx and apply the uncertainty relation $\Delta p\ \Delta x \geqslant \hbar$. Substituting for Δp, Δx one has, $R \geqslant \hbar/p\theta$. At 90 Mev, $p = 0.45$ Mc where M is the reduced mass of the system so $R \geqslant \lambda\!\!\!^{-}/0.45\theta$. θ represents the width of the peak due to the long range tail so here $\theta \sim 5° \simeq 0.1$ radian. Thus $R \sim 20\,\lambda\!\!\!^{-} \simeq 1.8 \times 10^{-12}$ cm which seems unduly long.

The purpose of this work is to investigate in greater detail the angular distribution of the differential cross section in the neighborhood of this peak. In the laboratory system, this corresponds to small angles in the forward directions when one counts neutrons by detecting the protons recoiling at right angles. With this in mind, a detecting system was built up which had improved angular and energy resolution. Scintillation counters were used instead of proportional counters because of their greater speed. This made it possible to use the full beam intensity at all times in spite of the low coincidence/singles ratio occasioned by narrowing the acceptable energy interval from 66-130 Mev to 85-95 Mev. A further contribution to the smallness of this ratio was the fact that the scintillation counters could count some neutrons directly due to proton recoils in the stilbene crystals. This effect, however, was small and the disadvantages due to it were outweighed by the advantage resulting from increased counter speed.

In order to allow an approximate normalization of the final results to the earlier work of Segrè and co-workers, measurements were made at 10° and 25° in the laboratory system as well as from 1° to 5°.

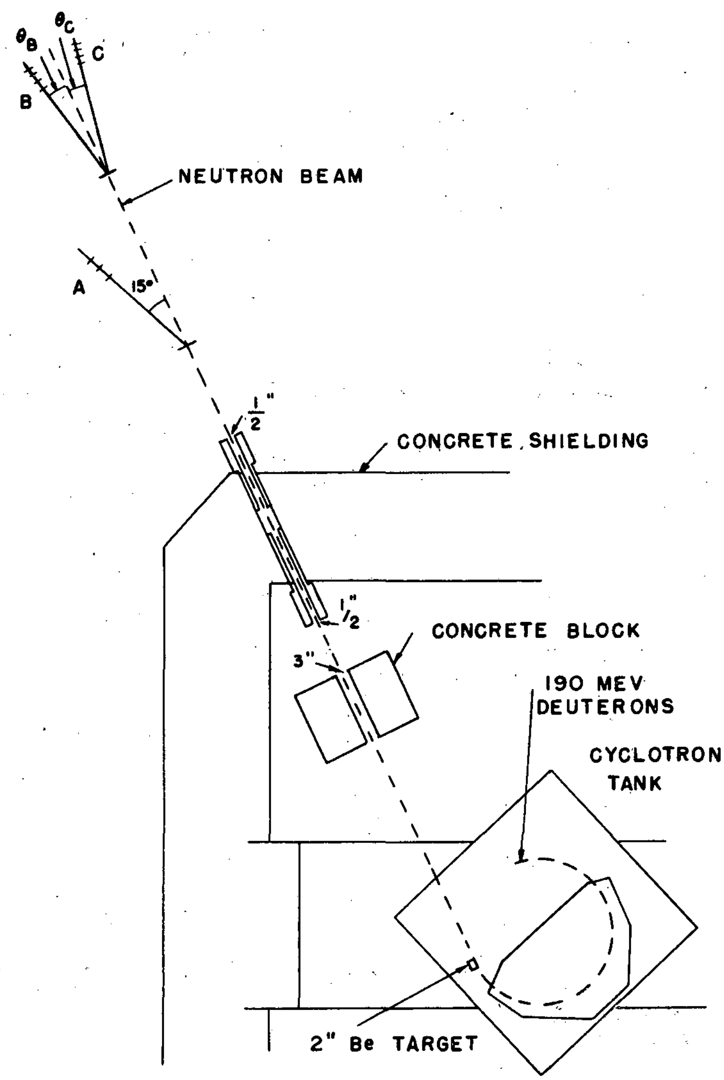
II. EXPERIMENTAL METHOD

A. Detector System

The neutron beam was formed by stripping 190 Mev deuterons on a 2-inch thickness of beryllium. The neutrons then passed through three successive collimators before reaching the counting region outside the ten foot thick concrete wall surrounding the cyclotron. A short distance from the wall a fixed polyethylene target was placed to furnish recoil protons for the monitor telescope which was fixed in position and angle throughout a day's run. Some five feet behind the monitor scatterer was placed the scattering table which contained the target holder and two counter telescopes. The scatterers used were always considerably larger than the beam and perpendicular to one counter telescope which we shall call "B" and at 6^{o} to the other which shall be called "C". "C" was used only during the last few runs when attention was concentrated on the range 1^{o} to 5^{o} and could cover only this range. "B", on the other hand, was used on all runs and could cover the range 0^{o} to 25^{o}. This arrangement is shown in Fig. 1. Note that "C" counts negative angles.

Thus, recoil protons emerging from the target at angles Φ_B and Φ_C are counted by "B" and "C" respectively. Simultaneously, the monitor, which shall be called "A", counts recoil protons from the monitor scatterer to record the beam intensity during this period.

By the method described in Section III, the counter telescopes "B" and "C" were made sensitive only to protons generated by neutrons of energy E in the range 85-95 Mev.



MU 655

FIG. 1

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To determine the effect due to carbon and background, runs were also made with a carbon target and a blank. For the angular range 1° to 5° the hydrogen effect was then determined by the relation $N = N_{CH_2} - \delta N_C - (1-\delta)N_B$ where,

N	=	hydrogen effect
N_{CH_2}	=	polyethylene counts
N_C	=	carbon counts
N_B	=	background counts
δ	=	.716

For larger angles the more general relation $N = \Upsilon \left[N_{CH_2} - \delta(\Phi) N_C - (1 - \delta(\Phi))N_B \right]$, where Υ = thickness of $CH_2/\cos\Phi$, was used since both target thicknesses and the ratio of polyethylene to carbon was changed. This was the result of demanding that at any angle the energy loss of a recoil proton of energy $90 \cos^2 \Phi$ Mev originating at the rear of the target should be 5 Mev. This is discussed further in Section III.

B. Tranformation to the c.g. System.

The number N measured in the above manner is proportional to the differential cross section $\sigma(\Phi)$ since the solid angle $d\Omega = d\psi \, d\cos\Phi$ is kept constant. Let us further define the angles:

Θ = angle of scattering of the neutron in the laboratory system.

Φ = angle between incident neutron and recoil proton in the c.g. system.

Between these angles there are the following relations:

$$\tan \Theta = (1 - \beta^2)^{1/2} \tan (\theta/2)$$

$$\tan \Phi = (1 - \beta^2)^{1/2} \cot (\theta/2)$$

$$d \cos \Phi / d \cos \theta = 1/4 \quad 1/1-\beta^2 \quad \frac{(1 - \beta^2 \cos^2 \Phi)^2}{\cos \Phi}$$

$$E_p = E_n (1 - \beta^2)/ (1 - \beta^2 + \tan^2 \Phi)$$
$$= E_n \cos^2 \Phi (1/1 + \frac{\beta^2}{1-\beta^2} \sin^2 \Phi)$$

In this experiment $\beta^2/1-\beta^2 = 0.045$ and $\sin^2 \Phi \leq 0.18$ so that the relativistic effect in the last equation is < 0.8 percent and may be neglected.

The differential cross section in the c.g. system may then be obtained by $\sigma(\theta) = \sigma(\Phi)\, d \cos \Phi / d \cos \theta$ since ψ, the azimuthal angle, is the same in both laboratory and c.g. systems.

III. DETAILS OF THE DETECTOR SYSTEM

A. Neutron Beam Collimation.

The collimation of the neutron beam was effected by three collimators. The first consisted of a cube of concrete approximately six feet on a side with a 3-inch diameter hole and located between the cyclotron and the surrounding concrete shield. The latter is ten feet thick and contains a 3-inch diameter neutron port. This port was further collimated on the inner end by a 3-foot long brass plug with a 1/2-inch square aperture. Since the end of the collimating system was 40 feet from the source and the latter was approximately a point source, the angular divergence in the resulting beam was less than 0.1°. This was confirmed by photographs taken 12 feet from the exterior collimator showing a spreading of 1/8 inch in that distance or about 0.05°.

B. Monitor.

The monitor telescope consisted of three scintillation counters in triple coincidence three feet from the monitor target and mounted at 15° from the beam direction. A copper absorber 1/8 inch in thickness was placed in front of the telescope to absorb recoil protons from low energy neutrons. It was placed in front of all the counters rather than between the second and third because it was more important to minimize the single counts due to such low energy recoils than to prevent Rutherford scattering losses in the absorber. The copper absorber together with the stilbene crystals of the first two counters defined the minimum energy necessary for a recoil proton to produce a true triple coincidence. This minimum energy was about 60 Mev. Before Run No. 8, this monitor was modified in such a way that its aperture was defined only by the second crystal for particles coming from the target. Thus, for the last two runs, its efficiency did not change and the results of these runs could be combined directly without the necessity of doing a statistical fitting. If the monitor efficiency does change from one run to the next, it usually does so in an unknown amount with consequent loss of information. Since low counting rate is a major difficulty in such an experiment as this, it was necessary to remove if possible any such sources of information loss.

C. Counter Telescopes.

The two counter telescopes "B" and "C" were identical in nature. They were mounted four feet from the target and each consisted of four scintillation counters together with two absorbers. The fluorescent crystals used in all the counters consisted of stilbene. The crystals for the first three counters were 0.100-inch thick and 1/2-inch square. The fourth counter crystal was 1/4-inch thick and 3/4-inch square. All crystals were mounted in 0.005-inch polished aluminum light tight boxes which in turn were mounted rigidly on the telescope base. 1P21 photomultiplier tubes were mounted at the other end of the aluminum boxes to collect the light. Each had an electrostatic shield at cathode potential covering all the glass envelope except for the aperture for the light pulses. The details of telescope "B" are shown in Fig. 2.

A proton of energy E_p would lose energy $\Delta E(E_p, t)$ in traversing a crystal, where t is the crystal thickness. A fraction of this energy $\epsilon \Delta E$ is converted into light quanta which enter the photomultiplier tube and are converted into photoelectrons. This photoelectric current is amplified and appears on the output as a fast ($\sim 0.01\ \mu$ sec.) negative pulse. This pulse is fed into a cathode follower with 20 Mc bandwidth and thence along 100 feet of RG63/U transmission line to the counting area. There the signal was used

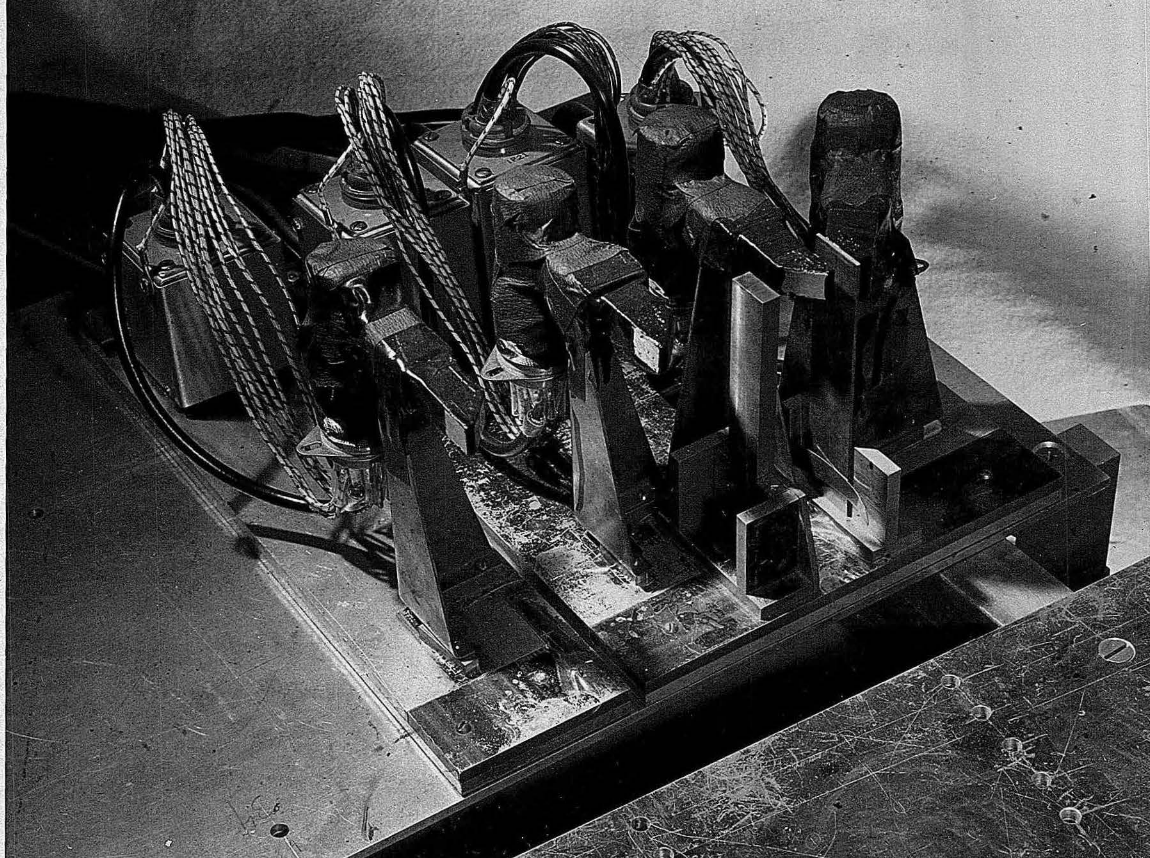


FIG. 2

OZ 956

to trip a three stage amplifier with positive feedback which produced a standard square pulse 25 volts high and 0.2 μ sec. long. The necessary signal input for tripping this amplifier was 0.1 volts.

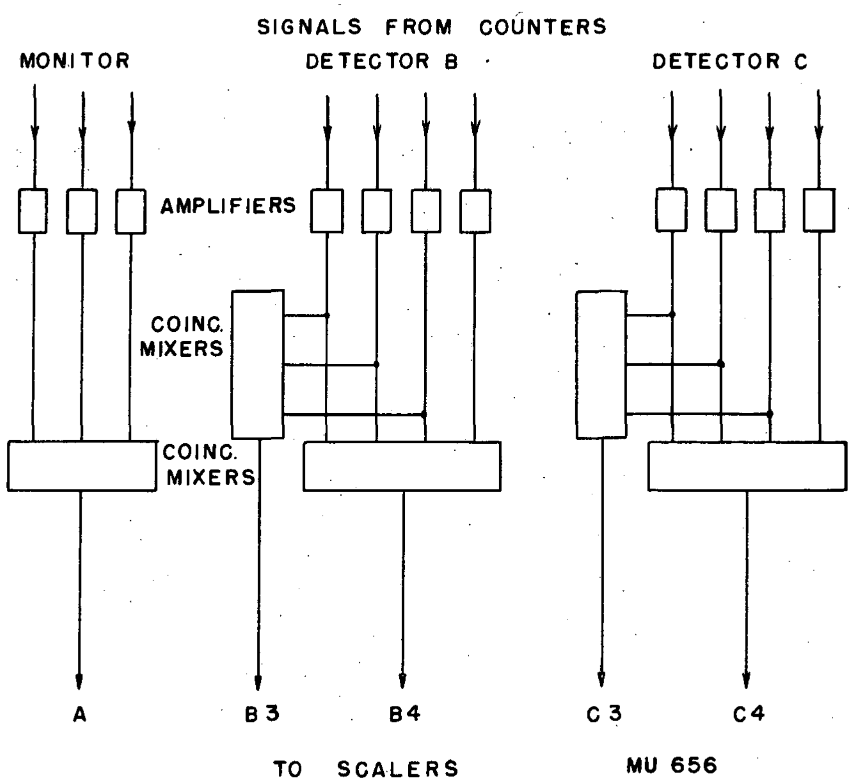
Thus, signals of uniform height and shape could be fed into the germanium diode mixer circuit which had a coincidence gate width of 0.1 μ sec. The coincidence signals were finally fed into standard scalers and registers. The scalers had a 10 μ sec. dead time.

D. Absorbers.

Each telescope contained two absorbers of accurately known thicknesses. A thick copper absorber was placed between the second and third counters. For a given detection angle Φ , its thickness was so chosen that a recoil proton of 85 $\cos^2 \Phi$ Mev originating in the center of the target would enter the third crystal with 2 Mev residual energy and thus be counted. These three counters were in triple coincidence. Thus the minimum energy required by a neutron to produce a triple coincidence was 85 Mev. A thin copper absorber was placed between the third and fourth counters, and as close to the latter as possible. It was of such thickness that a recoil proton originating in the center of the target had to have a minimum of 95 $\cos^2 \Phi$ Mev in order to enter the fourth crystal with 2 Mev energy. The signal from this counter was fed into a quadruple coincidence mixer. This is illustrated in Fig. 3.

Thus, any proton of energy 95 $\cos^2 \Phi$ Mev producing a count in the triple coincidence channel, which we shall call B3 (or C3 for telescope "C"), also produced a count in the quadruple coincidence channel, which we shall call B4 (or C4). Thus, the counts due only to protons in the energy range 85 $\cos^2 \Phi$ to 95 $\cos^2 \Phi$ were given by the expression $N = N_{B3} - N_{B4}$. This method of doing anti-coincidence seems preferable to doing the subtraction electronically

FIG. 3


SIGNALS FROM COUNTERS
MONITOR
DETECTOR B
DETECTOR C
AMPLIFIERS
COINC. MIXERS
COINC. MIXERS
A
B 3
B 4
C 3
C 4
TO SCALERS
MU 656

for two reasons. In the first place, the operation of an anti-coincidence circuit at this speed is not as dependable as that of a coincidence circuit. In the second place, any failure of the fourth channel during a run would immediately show up in the counting rate of B4 (or C4) and in the ratio N_{B3}/N_{B4} (or N_{C3}/N_{C4}) which should remain constant from one month to the next. On one occasion a failure in the electronics during a run was detected in this manner and the trouble rectified.

The absorber thicknesses were calculated to an accuracy of 0.5 percent using accurate tables of ranges and stopping powers available at this laboratory[4]. The thick absorbers were machined to an accuracy of $\pm$ 0.001 inch and the thin ones were rolled to an accuracy of $\pm$ 0.0002 inch. The thicknesses thus calculated are tabulated in Table I.

Since in this experiment the measurements were confined principally to small angles, E_p (E_n, Φ) did not vary much with Φ. Therefore, the effect of Rutherford scattering in the second absorber was neglibible since losses due to this effect are proportional to Zt/E_p^2, where t is the absorber thickness, while t was varied approximately as E_p^2.

E. Scatterers.

The carbon and polyethylene scatterers were 2-inches square and so mounted that the neutron beam passed through their centers. Thus all of the beam was intercepted by the target and the beam area defined the size of the source of recoil protons. Polyethylene was used rather than paraffin because of its much greater uniformity in density and mechanical rigidity.

The uniformity of density of the polyethylene was checked by the following method: A number of 1/2-inch squares cut from the sheet material to be used were placed in a water-alcohol mixture whose density could be adjusted to that of polyethylene. When this was done with 400 cc of solution, it was

TABLE I

Absorber Thicknesses in mg/cm^2 of Cu

Φ	Thick Absorber
0-1	7275
2	7258
3	7235
4	7204
5	7162
7	7056
10	6822
25	4805

Φ	Thin Absorber
0-2	1325
3-4	1319
5	1310
7	1289
10	1235
25	786

TABLE II

Scatterer Thicknesses in mg/cm^2

Φ	CH_2	C
0-2	583	694
3-4	579	692
5	576	687
7	568	678
10	555	660
25	412	471

found that the addition of 10 drops of alcohol or water would cause all the pieces to sink or rise, respectively. This leads to an estimated uniformity in density of 0.01 percent.

Next the variations in surface density of the sheet material to be used were checked and found to be < 0.5 percent. Since polyethylene can not be machined accurately, the various scatterers were laminated from pieces 0.002, 0.004, 0.010, 0.062 and 0.125 inches thick.

The uniformity in density of the carbon used was checked by machining accurately many 1/4-inch cubes from one sheet and weighing them. The standard deviation from the mean was found to be 2.5 percent. Since the carbon effect was ~ 25 percent, this was negligible.

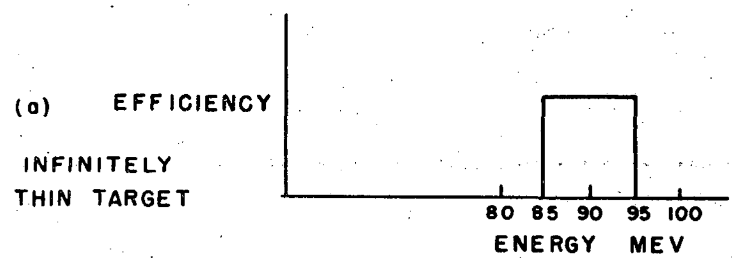
For a given angle of observation Φ, the thickness of the scatterers was such that a proton of energy 90 $\cos^2 \Phi$ Mev originating at the rear of the scatterer lost 5 Mev of energy. The effect of this finite scatterer thickness is to smear out the energy range for counting neutrons. For a zero thickness target a plot of counting efficiency vs. energy is shown in Fig. 4a. In Fig. 4b such a plot is also shown for a 5 Mev thick target.

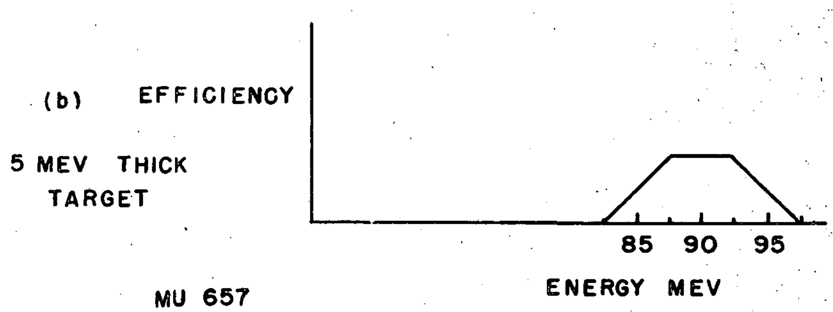
Since the peak in the energy distribution of the neutron beam is at 90 Mev and its width is considerably larger than the energy range allowed for counting, its effect may be disregarded.

F. Angular Resolution.

Since the angular divergence of the beam was negligible, the factors contributing to the angular resolution were the finite source and detector sizes and multiple scattering in the scatterer. Let Φ be the detection angle and Υ the initial scattering angle of a recoil proton. If $\alpha = |\Phi - \Upsilon|$, we can find an expression P (α) for the probability of counting the recoil proton.

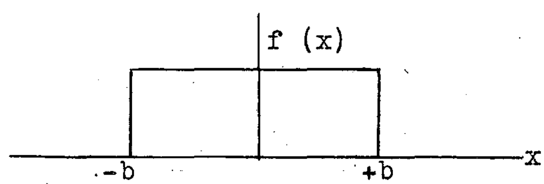
FIG. 4


(a) EFFICIENCY
INFINITELY
THIN TARGET
80 85 90 95 100
ENERGY MEV


(b) EFFICIENCY
5 MEV THICK
TARGET
85 90 95
ENERGY MEV

MU 657

Then, the width of P (α) defines the angular resolution of the system. Let us calculate this function. The detector angular width is 0.57° while that of the source is 0.71°. The effect of these two widths are similar in nature and they are nearly equal so to a first approximation we may set both equal to 0.64°. If $\sigma = (\overline{\sigma^2})^{1/2}$ is the root-mean square angle of multiple scattering for the carbon targets (σ for the carbon targets is larger than for the polyethylene targets), a calculation gives the result[5] $\sigma \sim 1.0^{\circ}$. Let us represent both source and detector by the same function f (x):

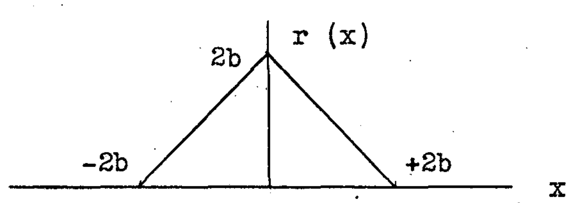


$2b = 0.64$

We can find a function representing the combined effect of the two, r (x), by the folding operation:

$$r(x) = \int_{-\infty}^{\infty} f(x-t)\, f(t)\, dt$$

Doing this integral we get the result:



Now the effect of the multiple scattering in the target can be introduced by another folding operation,

$$P(\alpha) = \frac{1}{\sqrt{2\pi\sigma^2}} \int_{-\infty}^{\infty} e^{\frac{-(x-\alpha)^2}{2\sigma^2}} r(x)\,dx = \frac{1}{\sqrt{2\pi\sigma^2}} \int_{-2b}^{+2b} e^{\frac{-(x-\alpha)^2}{2\sigma^2}} r(x)\,dx$$

This is a straightforward integral and yields the result:

$$P(\alpha) = o\sqrt{\frac{2}{\pi}}\, e^{-1/2\left(\frac{\alpha}{\sigma}\right)^2} \left\{ e^{-2\left(\frac{b}{\sigma}\right)^2} \cosh\left(\frac{2b\alpha}{\sigma^2}\right) - 1 \right\}$$

$$+ \frac{\alpha+2b}{2}\left[F\left(\frac{2b+\alpha}{\sqrt{2}\,\sigma}\right) - F\left(\frac{\alpha}{\sqrt{2}\,\sigma}\right)\right] - \frac{\alpha-2b}{2}\left[\pm\ F\left(\frac{2b-\alpha}{\sqrt{2}\,\sigma}\right) + F\left(\frac{\alpha}{\sqrt{2}\,\sigma}\right)\right]$$

$$\begin{array}{ll} + & o < \alpha < 2b \\ - & \alpha > 2b \end{array}$$

where $F(t) = \frac{2}{\sqrt{\pi}} \int_{o}^{y} e^{-y^2}\,dy$ is the probability integral.

Substituting $\sigma = 1.0^{\circ}$ and $2a = 0.64^{\circ}$ and using tables to get values of $\cosh(4b\alpha/\sigma^2)$ and the probability function, $P(\alpha)$ can easily be calculated. The result is shown in Fig. 5. It is seen that the angular resolution is approximately 1.3°.

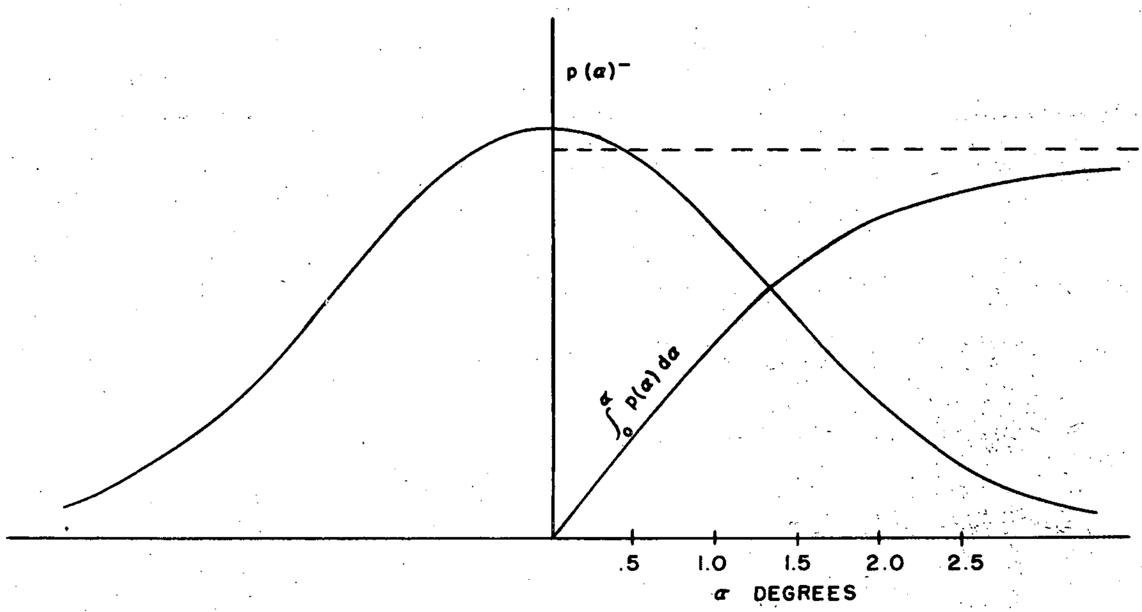


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FIG. 5

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IV. EXPERIMENTAL PROCEDURE

A. Adjustments and Tests of Apparatus.

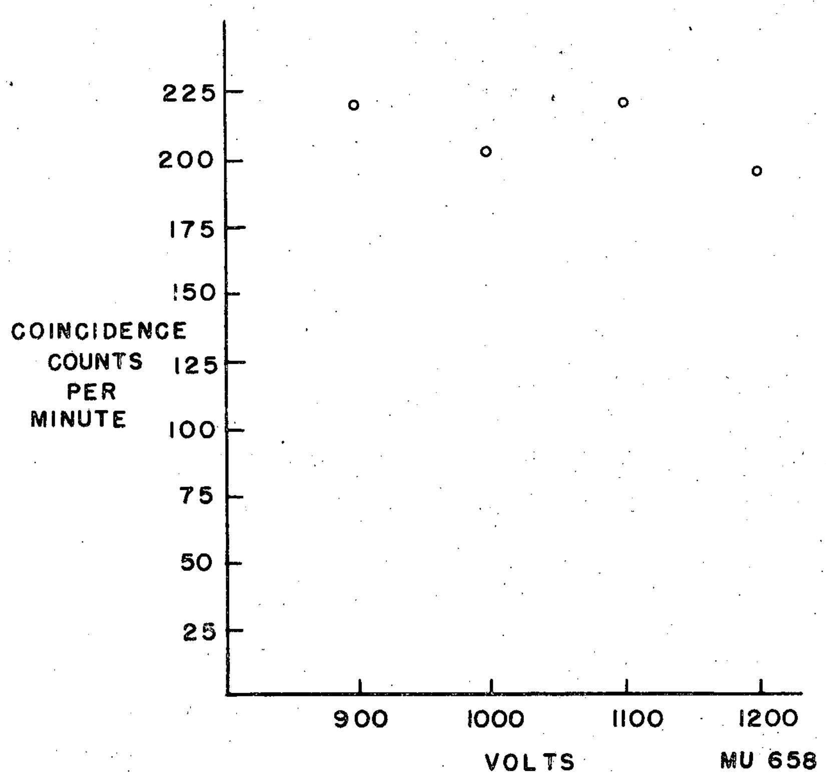
At the beginning of each day's run all counters were checked with a radium source to make sure they were counting satisfactorily. Next, in order to ascertain that all protons in the required energy range coming from the target were counted and nothing else, the coincidence counting rate vs. counter voltages was measured. Plateaus extending over 200 to 300 volts were normally obtained. A typical example is shown in Fig. 6. The counter voltages were set at the center of the plateau.

In order to check the accidental coincidence rate, the central counters in the triple coincidence telescopes were now moved out of line. This rate was always less than 1 percent of the true coincidence rate. Now, the accidental triple coincidence rate varies as the cube of the beam strength, so during the actual run when the beam level was down by a factor of ten from that used for testing, the accidental triple coincidence rate was completely negligible.

The critical parameter in determining the amount of saturation in the counters was the recovery time of the oscillator circuits. This was measured by feeding in short (0.05 μ sec.) pulses in pairs with variable separation and height. It was found that for pulse heights just sufficient to trip the oscillators this recovery time was about 1.2 μ sec. while for pulses twice this height or more it was 0.4 μ sec. Since the gain of the photomultipliers increases approximately by a factor of 2 for each 100 volts increase in voltage, and since all counters were set not less than 100 volts above the lower edge of the plateau, one can conservatively estimate that the recovery time was < 0.6 μ sec.

FIG. 6

COINCIDENCE VOLTAGE PLATEAU



Now let us consider the nature of the beam to see what this means in terms of counter saturation. The modulation frequency of the cyclotron is about 120 c.p.s. At the end of each modulation cycle the orbit of the beam is large enough so that it strikes the target on each revolution. This pulse lasts for about 100 μ sec. There is a fine structure due to the frequency of revolution and to radial oscillations. If it were not for the latter one would observe individual pulses 0.1 μ sec. apart for 100 μ sec. Actually, one observes a group of from one to three pulses so spaced, the group appearing once per μ sec.

Because of the low counting rates, the only kind of saturation one can expect is that occurring when a single count in one counter renders it insensitive for a time τ and within τ a true coincidence occurs but is thus not counted.

Here, this could only happen if both the single and the true coincidence count occurred in the same 0.2 μ sec. group but not if they occurred in separate groups or during the same 0.1 μ sec. pulse. From this information the fractional loss of counts $\Delta N/N$ can be calculated as a function of $\sum_i A_i$ where A_i is the observed single counting rate of the i-th counter in a telescope. All the A_i were measured during each run. Normally, $\sum_i A_i < 50$ c.p.s. for any of the three telescopes used and led to a value of $\Delta N/N < 0.005$.

There was also the possibility of accidental coincidences between a true double coincidence in the first two counters and a single count in the third. This effect is easily calculable if the double coincidence rates are measured also. It was found to be < 0.5 percent in all cases.

As a final preparation for a run, the 1/2-inch collimators were inserted and the equipment aligned accurately with respect to beam direction. The scattering table was mounted on parallel steel rails which could be displaced or rotated perpendicular to the beam. A cathetometer was aligned with the center line of the equipment and then the rails adjusted until it was centered with respect to the collimators. A final check was made by photographing the beam. In this manner the alignment could be done easily to within 0.1°.

B. Counting Procedure.

In order to minimize possible trends in systematic errors, each day's run of about ten hours was broken up into short runs of about a half hour's duration. During one of these N_{CH_2}, N_C, and N_B were measured for one angle. The measurements for a given Φ were made at different times throughout the run, alternating with those for other values of Φ.

The running time was apportioned among determinations of N_{CH_2}, N_C, N_B in such a way that each contributed equally to the statistical error in the determination of N. This gave maximum efficiency of counting time.

V. CALCULATION OF RESULTS, ERRORS, FITTING

The values of N for each angle were calculated using the difference formula previously given. From this formula one obtains the error formula

$$\Delta N = \gamma \left[\frac{N^2_{CH_2}(1 + N_{CH_2})}{n_{CH_2}} \quad \frac{\delta^2 N_c^2 (1 + N_c)}{n_C} \quad \frac{(1 - \delta)^2 N_B^2 (1 + N_B)}{n_B} \right]^{1/2}$$

n_i is the actual difference between triples and quadruples for target "i" while N_i is the ratio of this number to the monitor counts taken simultaneously.

To fit the data obtained in different runs, the following procedure was used: The weighted geometrical mean of the ratios $N(\Phi)$ for runs 3 and 7 to those of run 4 were calculated and used to adjust these runs to run 4. Then weighted averages of the values of N for each angle Φ calculated and the resulting distribution used as a base to which all other runs were fitted. In doing these fittings, one obtains formulae of the type $\overline{N}^i(\Phi) = \rho^i N^i(\Phi)$ where ρ^i is the fitting factor for run i and $\overline{N}^i(\Phi)$ is the fitted value of $N(\Phi)$ for this run. This process introduces a fitting error $N(\Phi)\Delta\rho$ since $\Delta \overline{N}^i(\Phi) = \left\{ \left[N^i(\Phi) \right]^2 (\Delta\rho^i)^2 + (\rho^i)^2 \left[\Delta N^i(\Phi) \right]^2 \right\}^{1/2}$. $\Delta\rho^i$ can be estimated from the statistical errors of the measurements which determine ρ.

The final results were then normalized to a smooth curve drawn through the results of Segrè and co-workers. These results are tabulated in Table III.

TABLE III

Φ	θ	$\frac{d\cos\Phi}{d\cos\theta}$	Run No.	2	3	4	5	7	7	8	8	9	9	$N(\Phi)$	$\sigma(\theta)$ in 10^{-27} cm^2
			Detector	B	B	B	B	B	C	B	C	B	C		
1	178.0	0.239				.418 ±.041	.422 ±.051	.377 ±.075	.405 ±.074	.393 ±.121	.459 ±.101	.414 ±.057	.474 ±.069	.419 ±.023	11.6 ±.64
2	175.9	0.239						.421 ±.071	.341 ±.069	.406 ±.062	.341 ±.064	.446 ±.042	.410 ±.035	.433 ±.022	12.0 ±.61
3	173.9	0.239		.510 ±.043	.477 ±.053	.491 ±.038	.464 ±.059	.521 ±.064	.478 ±.065	.458 ±.067	.445 ±.099	.505 ±.063	.466 ±.054	.486 ±.018	13.5 ±.50
4	171.8	0.240						.417 ±.063	.466 ±.086	.485 ±.067	.380 ±.058	.427 ±.040	.393 ±.036	.421 ±.021	11.7 ±.58
5	169.8	0.240		.417 ±.030	.451 ±.060	.440 ±.044		.387 ±.066	.481 ±.141	.376 ±.102	.508 ±.093	.413 ±.073	.380 ±.044	.425 ±.018	11.8 ±.50
7	165.7	0.241				.405 ±.052	.413 ±.042							.409 ±.033	11.4 ±.92
10	159.5	0.243			.353 ±.063	.342 ±.036								.345 ±.031	9.7 ±.83
25	129.0	0.268			.179 ±.027		.313 ±.035							.265 ±.024	8.1 ±.73

Note: Runs 1 and 6 were for instrumentation only.

VI. DISCUSSION OF RESULTS

By reference to Fig. 7, it is seen that the results agree satisfactorily with previous results in the region 170° to 130° as would be expected, but show a definite disagreement at the very small angles. Except for the value at 174°, the distribution appears to be essentially flat from 170° to 180°. One can hardly take the apparent peak at 174° too seriously since the statistics do not warrant it. Such a peak would indicate the existence of a very long-tailed tensor force. Neglecting this point, it does seem well established that there is no high peak at 180° and that therefore the range of the interaction is not much greater than the usual nucleon radius.

It is quite apparent that more work should be done on these measurements. The principal difficulty is in the low counting rate which is a direct result of the good angular resolution. The coincidence counting rates amounted to an effective rate of 50 per hour, where by effective rate is meant $(\overline{N}/\Delta\overline{N})^2$ for the day's run. The actual rate was five times this, the losses coming from the use of a difference method and the necessity of many fittings. An increase in neutron beam intensity together with the use of faster counting equipment would greatly aid in improving the results. With the present intensity, the effort involved in improving the statistical accuracy would be excessive.

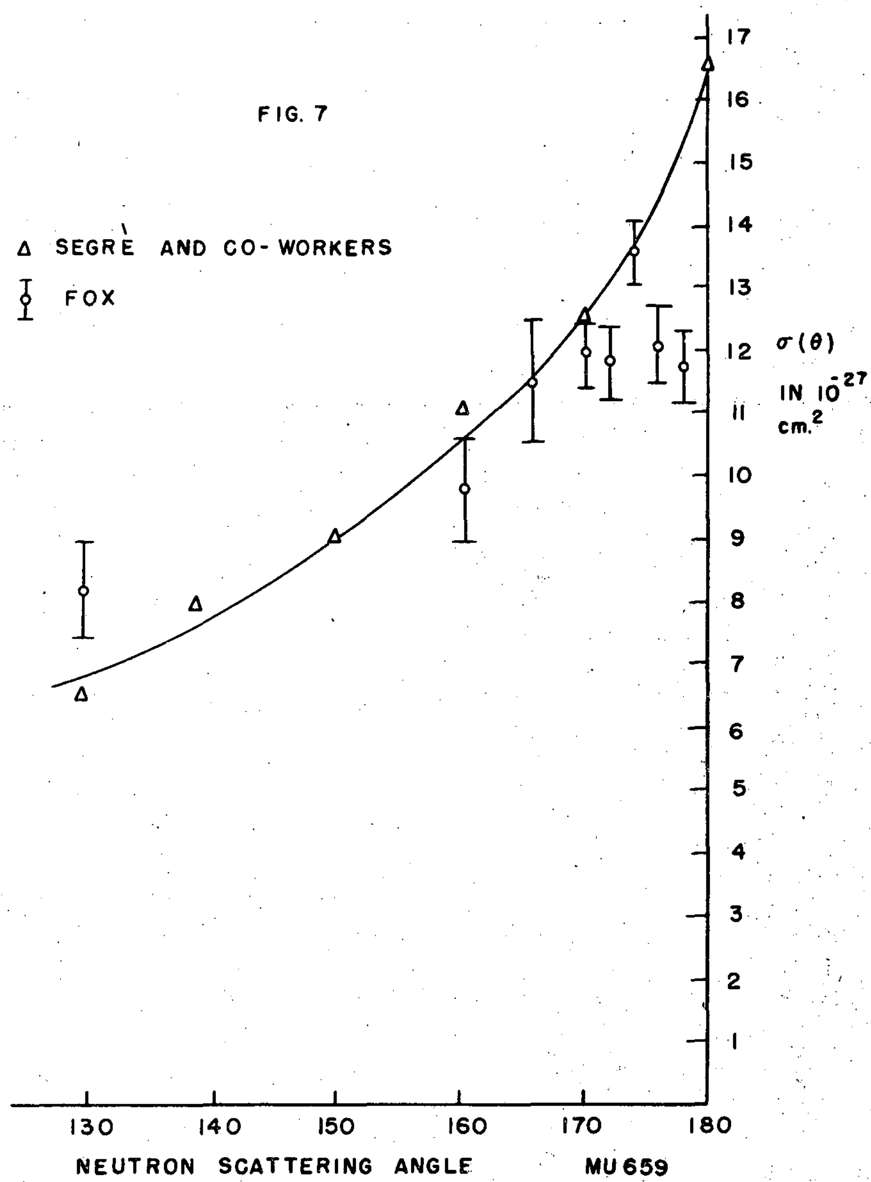


FIG. 7
SEGRÈ AND CO-WORKERS
FOX
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
σ(θ) IN 10⁻²⁷ cm.²
130
140
150
160
170
180
NEUTRON SCATTERING ANGLE
MU 659

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