Multiple Traversals of High Energy Particles in a Cyclotron Beam through Thin Targets *

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An experimental determination has been made of the average number of times that 340-Mev protons traverse various targets in the Berkeley 184-inch cyclotron. The numbers range from slightly above 1 for a 1-inch thick copper target to about 15 for an aluminum target 0.0015 inch thick. The results are compared with calculated values based on multiple scattering in the target and oscillations of the particles in the cyclotron. It is believed that the results can be adapted to apply to various particles of different energies in the cyclotron. Calculations are made on the energy distribution of beam particles which cause reactions in a target, and distributions are shown for several targets. The selection of targets for the production of high energy neutron beams is discussed. Histograms are presented showing the depth of radial penetration of the 340-Mev proton beam into various targets.

I. INTRODUCTION

IT has been known for some time that some of the high energy particles in a cyclotron beam pass through a thin target more than once. It has also been pointed out that the magnitude of this effect is probably dependent upon the amount of multiple scattering of the particles in the target.[1] In the work described in the preceding paper,[2] it became evident that the effective flux of particles through targets of different thicknesses might vary by an order of magnitude even when the targets were bombarded under identical cyclotron conditions. This has an obvious bearing on certain problems, such as the energy distributions of neutrons or other particles produced in a target, and the relative yields of particles or isotopes produced in different targets. Consequently, it was thought that some further investigation of the effect was called for.

II. EXPERIMENTAL PROCEDURE

Targets of different thicknesses and materials were placed in the path of the circulating beam of the 184-inch cyclotron and bombarded with 340-Mev protons at a radius of 80.5 inches. These targets were one inch high, from a few mils to one inch thick, and were held in place by a clamp one-half inch back from the edge of the target. With each target was mounted one or more aluminum foil monitors one and one-half mils thick. The edges of the monitors were carefully aligned to coincide with the edges of the targets. The relative amount of beam through each target was then determined by counting the Na^{24} activities produced in the aluminum monitors. The cross section for the production of Na^{24} in Al by high energy protons is constant (± 15 percent) in the energy region[3] 100 to 340 Mev.

In order to be able to compare the effective beams through different targets under similar cyclotron conditions, a device was constructed which would rotate four different targets successively into the beam, and which could be controlled from outside of the cyclotron shielding. This device is actuated by a coil which hangs with its axis perpendicular to the magnetic field of the cyclotron. When a current is passed through the coil, it rotates through 90° so that its axis is parallel to the magnetic field, and when the current is stopped, the coil falls back to its original position by gravitational action. This rotating action is transmitted mechanically to a windmill which has targets clamped on the ends of its arms. A mechanical positioner is added so that the windmill can end up only in one of four discrete positions, 90° apart. A single rotation through 90° can be accomplished in a time of the order of one second.

With the targets and monitors mounted on the target rotator, the assembly was inserted into the cyclotron and bombarded with protons. The constancy of the cyclotron beam during the five minutes or so that a given target was bombarded was observed with ionization chambers inside the cyclotron shielding which measured the general level of radiation from the cyclotron and target. It was found by comparison of the ionization chamber readings with the counting rates of neutrons produced in the targets that the ion chamber readings could be used to determine the constancy of the beam through the target to about 10 percent. The transition from one target to another was accomplished in a time of the order of one second, and it is necessary to assume only that the cyclotron operating conditions do not change rapidly during this period. Actually, it was quite easy to hold operating conditions steady within 10 percent for twenty minutes or more during which a set of four targets could be bombarded. Thus, in each run four targets were bombarded with all cyclotron conditions the same except the nature of the target itself. At the end of the run the monitors were allowed to decay for about 24 hours to allow the 2-hr F^{18} and shorter lived activities to die out, and then the 15-hr Na^{24} was counted with a chlorine quenched Geiger-Mueller tube and related circuits. When targets of atomic number greater than aluminum were bom-

* This work was carried out under the auspices of the AEC.
[1] Helmholz, McMillan, and Sewell, Phys. Rev. 72, 1003 (1947).
[2] W. Knox, Phys. Rev. 81, 687 (1951).
[3] R. L. Folger and P. C. Stevenson (to be published).

Table I. Data obtained by direct comparison of activities produced by 340-Mev proton beam in monitors attached to different targets. In each run the four targets were bombarded under identical cyclotron operating conditions.

Run	Target	Thickness in inches	Multiple scattering angle in milliradians	Relative flux through target
I	Al	0.0015	0.48	9.3
	Al	0.0115	1.33	5.3
	Al	0.126	4.4	2.0
	Al	0.758	10.8	1.00
II	Be	0.750	5.0	0.92
	Al	0.160	5.0	1.08
	Cu	0.024	4.9	1.02
	Pb	0.009	5.0	0.97
III	Be	0.25	2.9	4.5
	Al	0.25	6.2	1.9
	Cu	0.25	16.0	1.4
	Pb	0.25	26.6	1.00

barded, the monitors were shielded from the targets with other aluminum foils to prevent recoils or fission fragments from contaminating the monitors.

Monitors were placed on both the front and back of all thick targets (>1/2 in.) and some thin targets (⩽1/2 in.). In four of the thick target cases the back monitor read from 10 to 25 percent less than the front monitor after correction for attenuation. In all other cases the two monitors agreed within 10 percent. The average value of the activities in the two monitors was used. This effect probably depends on the alignment of the edge of the target with the beam direction. From the distribution of activity in the monitors it can be estimated that a one degree misalignment of a one-inch target would cause about 15 percent of the beam to miss one of the monitors. Scattering also tends to cause some of the beam to miss the back monitor.

III. CALCULATIONS AND RESULTS

Using the above procedure data were obtained in the form of groups of four values for the Na^{24} activity observed in the monitors attached to four different targets bombarded under the same cyclotron conditions. This activity was interpreted as being proportional to the actual flux of particles traversing the target under consideration. It was found that the flux varied by as much as a factor of 10 in comparing a thick target to a thin target.

It was assumed that the proper variable to use as a basis for comparison of targets of different thicknesses and different atomic numbers was the root mean square multiple scattering angle of the target to 340-Mev protons. The formula used for the plane projected mean square scattering angle was

$$\langle\theta^2\rangle_{\text{Av}}=8\pi Z^2e^4Nt\frac{E^2}{(E^2-E_0{}^2)^2}\ln(183Z^{-\frac{1}{3}}),$$

where E and E_0 are the total and rest energies of the bombarding proton and the other symbols refer to the target. This is taken from Williams' scattering formula[4] using the nuclear radius and Bohr radius for cut-off parameters, with some refinements for shielding. In order to verify this assumption, targets of Be, Al, Cu, and Pb, of thicknesses calculated to give the same multiple scattering angle, were compared in one run and; it was found that the fluxes through these targets were the same within 10 percent (see Table I, Run II). The 10 percent variation is probably about the reproducibility of the technique for individual results; the variations did not show any trend with respect to atomic number or thickness.

Table I shows the results of several individual runs. Each of these groups of four values can be plotted in arbitrary units as relative beam through a target *versus* the multiple scattering angle of the target. The actual number of times that the beam circulated through the target, or the beam which would be observed with a target thick enough to stop the beam completely, is still unknown. However, since it is known that the multiple scattering angle is the proper variable with which to compare targets, the different groups can be plotted on the same graph and the vertical scale for each group can be adjusted arbitrarily until all of the values lie on a smooth curve. Furthermore, it can be assumed that if the data were carried out to targets thick enough to stop the beam, the activity in the

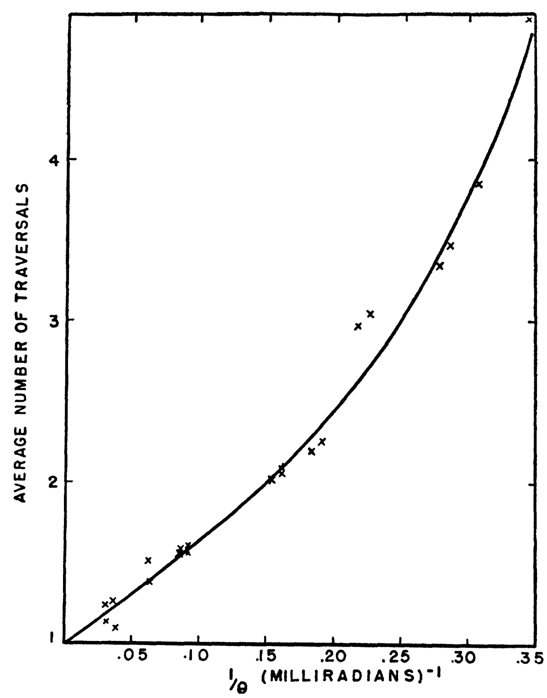

Fig. 1. Average number of traversals of 340-Mev proton beam through various targets. Abscissa is the inverse of the root mean square multiple scattering angle of the target to the beam. The vertical scale has been adjusted so that the curve extrapolates to a value of one.

[4] E. J. Williams, Proc. Roy. Soc. (London) **169**, 531 (1939).

monitor would represent the actual current accelerated by the cyclotron. The particles would be accelerated, would strike the target, and none of the particles would circulate in the cyclotron and strike the target a second time. If one now considers the average number of traversals of the particles in the beam through targets, it is seen that the data extrapolated to very thick targets should approach a value of one. Figure 1 shows the thick target data plotted *versus* the inverse of the multiple scattering angle adjusted to approach a value of unity. The extrapolation to zero is short and not very critical. In this way an absolute scale is determined empirically for the average number of traversals of particles in the beam through various targets. The uncertainty in this scale, because of the extrapolation to thick targets, is of the order of 5 percent. The final data are presented in Fig. 2.

Some of the monitors were cut up into thin strips parallel to the edge of the target, and these strips were counted separately in order to determine the extent of radial penetration of the beam into targets. Histograms showing the specific activity of the monitor *versus* the distance from the edge of the target are presented in Fig. 3. The total area in each histogram has been made proportional to the average number of traversals of the beam particles through the target. The distributions are only valid out to 1.25 cm for the target thickness indicated. Between 1.25 and 2.5 cm from the edge of the target, the beam passed through the target clamps ($\frac{1}{4}$ inch of brass) as well as the target and monitors.

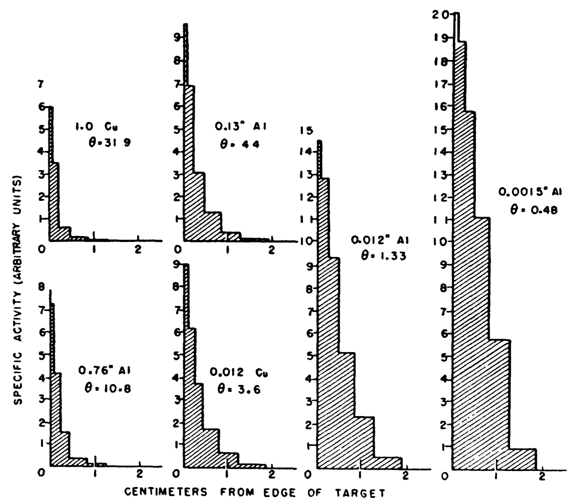

FIG. 3. Distribution of activity in monitors attached to various targets as a function of distance from edge of target. The distributions are only valid up to 1.25 cm for the target thickness indicated (see text). The multiple scattering angle of each target to 340 Mev protons is indicated near each histogram. The total area of each histogram is proportional to the average number of traversals of the beam through the corresponding target. (On the figure read 1.0″ Cu, 0.012″ Cu, and $\theta=4.4$.)

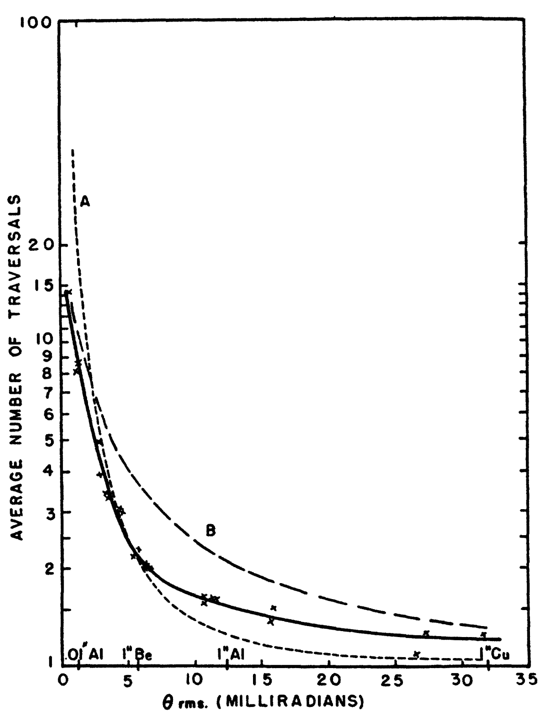

FIG. 2. Average number of traversals of 340-Mev proton beam through targets as a function of multiple scattering angle of target. Solid line is a smooth curve drawn through the experimental points. Dotted line (A) is a theoretical curve based on removal of particles from beam by gas scattering. Dashed line (B) is an approximate calculation for removal of particles from beam after scattering in target.

IV. DISCUSSION

Two calculated curves can be compared to the data. Theoretical calculations have been made on the removal of particles from the bevatron beam by gas scattering.[5] The type of function for gas scattering in the bevatron, which is comparable to the present data, is $(1+k/\theta^2)$, where θ is the multiple scattering angle of the particles by the gas in one traversal of the bevatron.[6] A function of this type (Fig. 2, curve A) falls off more rapidly with increasing θ than does the experimental curve. This is to be expected, since the mean free path of high energy particles in the bevatron is long with respect to the wave length of vertical oscillations. In the cyclotron, all of the scattering in the target occurs in such a short distance that only the resultant multiple scattering distribution is important in determining the number of particles lost from the beam. Thus, one would expect particles to be lost faster in the bevatron gas scattering case than in the cyclotron target scattering case.

An absolute multiple traversal curve based on certain simplifying physical assumptions can be calculated. From the radial variation of the magnetic field in the cyclotron, the wavelength of vertical oscillations of particles in the beam, and thus a relationship between the projected vertical scattering angle and the maximum amplitude of oscillation allowed by the dee, can

[5] N. M. Blachman and E. D. Courant, Phys. Rev. 74, 140 (1948); Phys. Rev. 75, 315 (1949).
[6] A. Garren (private communication).

be obtained. Furthermore, the number of particles acquiring vertical oscillations greater than those allowed by the dee and thus removed from the beam after each traversal of the target can be calculated, if the following assumptions are made. First, the particles as they approach the target for the first time have approximately a gaussian distribution of amplitudes of vertical oscillation with a half-width of about half the maximum allowed by the dee. Second, the particles on passing through the target acquire an additional gaussian distribution of amplitudes of vertical oscillation because of multiple scattering in the target. The width of the resultant distribution can be taken as the square root of the sum of the squares of the widths of the individual distributions. Third, energy loss in the target and scattering in the horizontal plane do not remove particles from the beam. If the path of a particle with losses of the order of 100 Mev at 80.5-inch radius is plotted, it is seen that the particle will describe an approximate circle of much smaller radius but with its center displaced so that the particle comes back to within a few tenths of an inch of where it struck the target. This can be regarded as an enormous radial oscillation of the particle about a smaller equilibrium orbit which is centered in the cyclotron. The maximum of this oscillation will precess until the particle strikes the target again. In most cases the effect of scattering in the horizontal plane is small compared with the effect of energy loss in the target on the resultant orbit of the particle. Fourth, the root mean square amplitude of oscillation of the particles can never exceed a value obtained by compounding the maximum amplitude passed by the dee and the amplitude acquired in one passage through the target. Using these assumptions and taking into account absorption in thick targets, one can calculate the rate of removal of particles from the beam and the average number of traversals expected through a given target. For thick targets in which the root mean square scattering angle in one traversal of the target is comparable to the maximum allowable scattering angle, approximately a constant fraction of the beam survives after each traversal of the target. For thin targets the survival fraction is not constant but gradually decreases to a constant value as the number of traversals increases.

The result of these calculations is shown in Fig. 2, curve B. The calculated curve agrees with the data fairly well for thin targets and for thick targets, but it is high in the intermediate region by a factor of up to 1.7. The agreement for thin targets is fortuitous since in this region the calculated curve is strongly dependent upon the first assumption. However, the general shape of the curve and the approximate magnitude of the absolute calculated values is in agreement with the observed values. Evidently, particles are lost from the beam slightly faster than can be accounted for with the above assumptions. This type of calculation could be considered as giving a maximum value for multiple traversals.

In Fig. 3 the distribution of the monitor activity as a function of the distance from the edge of the target is shown for several targets. It can be seen that the beam penetrates more deeply into thin targets than into thick targets. For the one-inch copper target, about 80 percent of the beam is concentrated in the first two millimeters from the edge of the target. For the thinnest target, 0.0015-inch aluminum, about 30 percent of the activity is in the first 2 millimeters. It should be noted that even though only a few percent of the total effective beam is passing through the target clamps in the case of the thin aluminum target, this is almost equal to the total beam passing through the one-inch copper target.

V. CONCLUSIONS

These results have several obvious implications. First, if a large effective beam or high specific activity in the target is desired, a thin target should be used. However, if the largest total production of particles or activity is desired, a thick target should be used. The decrease in yield as a result of less target atoms in the path of the beam is only partially compensated for by the increase caused by multiple traversals. Second, in calculating the energy distribution of particles which react in the target, one must take into account that some of the particles have passed through the target several times. Third, one must consider the possibility of an appreciable fraction of the beam penetrating deeply into the target. This is particularly important when very thin targets are used and part of the beam penetrates the target holder, which may be much thicker than the target. In this case a significant fraction of the interaction of the beam with the target may occur in the target holder.

It seems reasonable that these results should apply to other particles, which are used at about the same radius in the 184-inch cyclotron, if the proper multiple scattering angle is calculated. The calculation of the multiple scattering angle takes into account the energy, mass, and charge of the particle. At a different radius, or in another cyclotron, the shape of the magnetic field, and thus the dependence of number of traversals on multiple scattering angle, would be different. In this case, an approximate calculation as described above or another experimental determination must be made. The accuracy of the calculation is indicated by a comparison of curve B with the experimental curve in Fig. 2.

If these results are accepted as applying to deuterons, one can estimate the additional average energy loss of the deuterons in the target because of multiple traversals. This results in a lowering of the peak of the predicted energy distribution of the neutrons or protons from stripping. If this correction is made, the predictions come into slightly better agreement with the experimental results on the energy distributions of protons[7] and neutrons[8] from the stripping of 190-Mev deuterons. The low energy tail on the neutron distribution also can be explained in this manner. The correction amounts to a lowering of the peak energy by 2.5 Mev in the proton experiments in which a $\frac{1}{16}$-inch copper target was used, and by about 4 Mev in the neutron experiments in which a $\frac{1}{2}$-inch beryllium target was used.

An estimate of the actual energy distribution of the particles interacting with the target can be made. Using the calculation described above plus a form factor which makes the calculated curve fit the experimental results, the fraction of the beam which passes through the target n times can be estimated. For thick targets this amounts to about the same as taking the experimental value from Fig. 2 for the average number of traversals and using the terms of a geometric series which sums to this value to represent the survival fraction of the beam. The distribution is shown for several targets in Fig. 4a. This procedure assumes a monochromatic incident beam. It is known that radial oscillations occur in the cyclotron which must have some effect on the energy of particles which strike the target.[1] Although there is little direct experimental evidence to fix the magnitude of this effect, it is thought that the amplitude of radial oscillations is of the order of 2 inches at a radius of 80 or 81 inches in the 184-inch cyclotron. Since a particle should strike the target near the maximum of its oscillation, the effective radius of curvature of the particle when it strikes the target is of the order of from 0 to 2 inches less than the nominal radius of curvature. If the assumption is made that the radii of curvature of the particles are uniformly distributed through this range, then there is a width of about 15 Mev in the incident 340-Mev proton beam, and about 10 Mev in the 190-Mev deuteron beam. The effect of superimposing this width on that of ionization energy loss, including multiple traversals, is shown in Fig. 4b. The tails of the distributions in Fig. 4 for very large energy degradation should not be taken too seriously. The changes in scattering, rate of ionization energy loss, and attenuation with energy have been neglected.

Combining the factors of neutron yield per atom[2] as a function of Z, barrier energy loss,[9] ionization energy loss in target and multiple traversals, one can make the following predictions about the neutron beam from the stripping of 190 Mev deuterons. A thin target of low Z should give the highest peak energy but low yield. A very thin target of high Z should give the least spread in energy because of ionization loss in the target but very low yield. A thick target of low Z should give the highest yield but wide energy distribution. For optimum performance combining low barrier energy loss, narrow distribution, and high yield, a beryllium target about $\frac{1}{4}$ or $\frac{1}{2}$ inch thick should be used. In this particular case one must consider that the stripping process itself gives a broad neutron energy distribution, so that little is gained by going to a thin target of high Z, which gives the sharpest incident beam. Similar considerations may be applied to the selection of targets for other purposes.

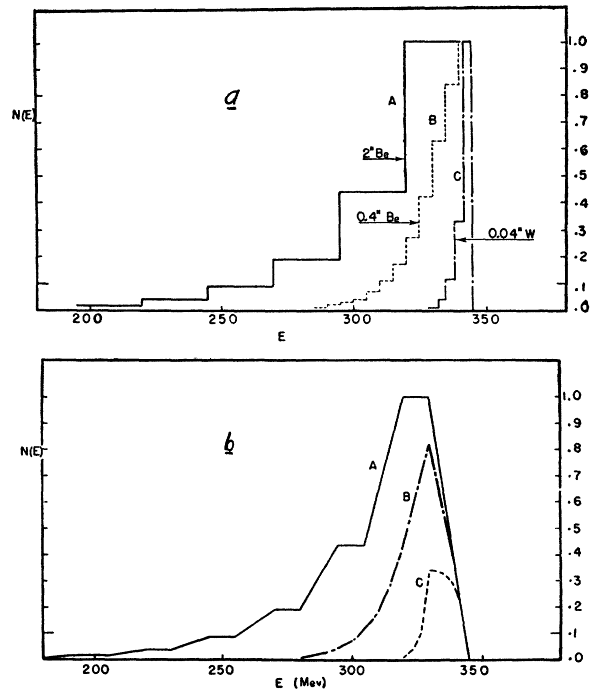

FIG. 4. Spread in energy of proton beam from ionization energy loss and multiple traversals. $N(E)$ is proportional to the number of particles which have an energy E as they pass through the target. (a) The incident beam is assumed to be monochromatic at 345 Mev. (b) The incident beam is assumed to be square in energy distribution with a maximum of 345 Mev and a width of 15 Mev from radial oscillations. Curve A is for a 2-in. beryllium target, curve B for a 0.4-in. beryllium target, curve C for a 0.040-in. wolfram target.

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[7] Chupp, Gardner, and Taylor, Phys. Rev. **73**, 742 (1948).
[8] Hadley, Kelly, Leith, Segrè, Wiegand, and York, Phys. Rev. **75**, 351 (1949).
[9] R. Serber, Phys. Rev. **72**, 1008 (1947)