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THE ARGONNE 60-IN. SCATTERING CHAMBER

by

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ABSTRACT

The 60-in. scattering chamber used with the external beam of the Argonne 60-in. cyclotron is described. The scattering chamber permits operation over an angular range from 4° to 176° with an accuracy of ± 3 min. of arc. The geometrical factors involved in the measurement of cross sections are known to $\pm 0.1\%$ or better. The angular positions of the detectors, the target changer, and an absorber foil system in front of the detection units are operated by remote control so as to permit continuous operation of the cyclotron when these parameters are varied. It is possible to operate several detectors simultaneously; and in order to permit angular correlation studies, the angular position of one detector can be varied by remote control with respect to the other detector units. A summary of some of the experimental work performed with this instrument is given.

INTRODUCTION

This report describes the scattering chamber used in the experimental program with the external beam of the Argonne 60-in. cyclotron. The cyclotron produces external beams of 21.6-Mev deuterons, 43-Mev alpha particles, and 10.8-Mev protons. At present there is no magnetic analysis of the external cyclotron beam.

The scattering chamber has been primarily designed for the accurate measurement of differential cross sections. For this purpose, it was considered necessary to measure differential cross sections to about 1%, which in turn makes it necessary to measure the angle of scattering to a high degree of precision. Furthermore it appeared desirable to be able to work at small angles. The instrumentation had to be adaptable to the measurement of angular correlations and it was necessary, in view of the high neutron flux in the experimental area, to operate the scattering chamber by remote control. A brief discussion of these requirements is useful in order to determine the various design considerations.

A. Measurement of Absolute Cross Sections

Absolute cross sections must be measured in a great number of experiments such as angular distributions of particles elastically scattered by nuclei, and pickup and stripping reactions. The measurement involves the determination of the geometrical factors involved in scattering, of the number of particles incident upon the scatterer, and of the number of target nuclei per cm^2 . As far as the scattering chamber is concerned, this means that it is necessary to know accurately both the subtended solid angle $d\omega$ and the angular position of the target with respect to the beam. Furthermore, since in many instances the cross section varies very rapidly with angle, the subtended angle must be small. If this is achieved by reducing the dimension of the detecting aperture some uncertainty will be introduced through effects of penetration of the edges of

the slit. Of course the subtended angle can be small only if the beam is well defined and has a fairly small cross section and a small angular divergence. In order to accommodate the changes in cross section, it is desirable to be able to vary $d\omega$ readily and this is done most easily by changing r , the distance from the detector aperture to the scattering center, provided one does not change the scattering angle when one changes r and provided that r is readily measured to an accuracy of about 0.1%.

B. Angular Range

In order to be able to measure at small angles, it is necessary that the dimensions of the detection unit be small compared to the distance r . If one uses a photomultiplier unit as the detector, it is usually not practical to work with a unit of less than 1 in. radius. Therefore, in order to work at an angle of 4° , the finite diameter and divergence of the incident beam as well as the multiple scattering in the target require a minimum value of $r = 45$ cm. Of course the comparison with theory requires a very high degree of precision in the measurement of the angle of scattering when one works at small angles. This is immediately obvious when one makes a comparison with Rutherford scattering and attempts to find deviations from the variation with $\text{cosec}^4 \theta / 2$ but it is equally necessary in measurements of angular distributions of reactions such as (α, t) reactions for which the momentum-transfer vector is large even at small angles.

C. Angular Correlation

In angular correlation experiments it is usually necessary to vary the angle between two detectors, one of these remaining fixed with respect to the incident beam. In our present experimental program it appears sufficient to have the moving detector move in the plane of scattering. In some types of experiments it may be necessary to have a fairly small $d\omega$

and large $d\omega'$. This usually requires as large a ratio r/r' as is practicable.

D. Remote Control

Remote control of a number of the variables in a scattering experiment is necessary since the possible health hazard makes the experimental area inaccessible except when the rf power of the cyclotron has been shut off. It is, in general, not desirable to turn the rf power off in order to change parameters since this interferes with stable operation of the cyclotron and produces an appreciable time loss as well as possible changes in the mean energy of the beam, which can be obnoxious in some experiments. The essential parameters which we wished to control in the present experimental setup were:

- a) the angle of observation of the scattered beam;
- b) change in relative position of two or more detectors;
- c) change of target in the case in which foils are used as targets;
- d) variation of particle energy by placing various absorbers in the beam in front of the collimating system; and
- e) insertion of different amounts of absorber in front of the detector.

On the basis of these requirements, the diameter of the chamber was chosen to be 60 in. The basic principle of the design is similar to that of the 60-in. scattering chamber at Princeton.¹ The essential parts are a collimator tube and a scattering table which are supported from a strong frame. Adjustments are provided to position the collimator so that its axis intersects, and is perpendicular to, the axis of rotation of the scattering table. The table carries the detection units and the scatterer. The scattering volume is enclosed by a vacuum can which has been suitably reinforced to minimize deflections. However, such deformations as do occur cannot affect the relative positions of the essential components, since the vacuum can is attached to the working parts only by

Fig. 1. Floor plan of cyclotron.

flexible bellows and the whole system of working parts is supported by a framework that has a sufficient number of adjustments to permit alignment of the collimator with the cyclotron beam.

The first section of this paper deals with the construction of the mechanical equipment; the second section describes the detection and particle identification as well as the remote controls; and the last section gives some of the results obtained during the initial operation.

I. DESIGN AND CONSTRUCTION OF THE 60-IN. SCATTERING CHAMBER

The floor plan of the cyclotron and part of the experimental area is shown in Fig. 1. The external deflected beam is focussed into the experimental tunnel by means of any one of 3 sets of quadrupole magnets. Two sets of deflection magnets which can steer the beam in both the horizontal and vertical planes are provided. An energy-degrading unit is located at the focal point of the first set of quadrupole magnets. The deflection magnet which permits the use of ports other than the 0° one is not ordinarily used in experiments with the scattering chamber.

A cross section of the 60-in. scattering chamber is shown in Fig. 2. Figure 3 is a photograph of the equipment. For the purposes of description, the scattering chamber is resolved into a number of subassemblies:

- a) the scattering table and spindle housing;
- b) the collimator and collimator adjustments;
- c) the vacuum chamber and vacuum system;
- d) the supporting framework;
- e) the collector cup assembly;
- f) the detector arms;
- g) the detection unit; and
- h) the target foil changer.

Fig. 2. Cross-sectional drawing of scattering chamber.

Fig. 3. Photograph of scattering chamber.

The last three will have to be described in some detail. Finally, the alignment procedure and the accuracy of the equipment will be considered.

A. Scattering Table and Spindle Housing

The scattering table carries the target as well as the detector units. Since our design requirement is to obtain $d\omega$ to approximately 0.3%, it is necessary to measure the distance r from the scattering center to the detecting aperture to approximately 0.1%. The table is also used to measure the angle between the beam and the normal to the scattering foil, which is important with respect to the number of target nuclei per cm^2 , and to measure the angular position of the detector with respect to the incident beam. It is obvious, when one considers the $\text{cosec}^4 \theta/2$ term in Rutherford scattering, that the precise measurement of this angle in the forward direction is very important. This is especially true when one is concerned with small deviations from rapid variations at these angles as, for example, in (p,p) or (α , α) scattering. However, very rapid variations in cross sections do occur at practically all angles, as becomes clear from the cross section of elastic scattering of 43-Mev alpha particles by zinc (Sec. III). In the design of the table and spindle housing, it is therefore important that the axis of rotation be well defined, that the table be accurately perpendicular to this axis, and that the circumference of the table be concentric with the axis. The angles are read from graduations on the circumference of the table and the accuracy of these graduations has to be comparable to that expected from the assembly as a whole, viz., ± 1 min. of arc, for a single reading. The table should be actuated by remote control in order to change the angle of observation without disturbing the operation of the machine. It is of course also necessary to operate it manually in order to make the necessary checks of alignment.

The table is shown in Fig. 4 with the equipment used to engrave the graduations. A cross-sectional drawing of the table and spindle housing

Fig. 4. Table graduation arrangement.

is shown in Fig. 5. The outside diameter of the table is 57.294 ± 0.005 in. Therefore, 1° of arc corresponds to 0.500 in. along the circumference. The axis of rotation is determined by the preloaded bearings a and b which are press fitted to the table shaft. The locating of the table is achieved through surface c, which was machined at the same time as the outside diameter of the table. The surface c was specified to be perpendicular to the top surface of the table. A step was cut on the outside circumference about $\frac{9}{16}$ in. below the top to permit installation of a gear rack. The arms are located with respect to the axis through the arrangement described in part F of this section. The target holder is supported from the table by means of a platform with three legs. The legs are located in recess d. The inside diameter of this recess is between 16.125 and 16.124 in. and concentric with the axis of the table.

The table is supported through frame F (Fig. 2) by means of legs L. The legs have pads for adjustment. The table stem is connected to the vacuum chamber through sylphon bellows s. The table is driven through gears g_1 and g_2 , connected through a mechanical clutch h to speed reducer r and from there to the remote-control drive. The table can be held in position through the friction lock ℓ .

The table could have been graduated by use of the fact that, to a good approximation, the distance per degree of arc along the circumference is 0.500 in. However, a slight systematic error in measuring the length would have resulted in an appreciable error near the end of the graduation. A systematic error of 0.03% would have resulted in an error of 7 min. of arc. This assumes that the surface c and the outside circumference are truly concentric. An error in concentricity of 0.004 in. would add about 1 min to the error. An additional uncertainty would be introduced by the necessity to determine where the previous graduation mark was to better than 0.001 in. This can easily result in an added, and quite considerable, systematic error. In order to stay within a total error of ± 1 min. of arc

Fig. 6. Arrangement of cutter for graduating the table.

between any two graduations, it was decided that it would be best to transfer the graduations from a previously graduated circle. The circle of a reflection goniometer was used as the master circle. Figure 4 shows the graduation setup. The table was mounted on the rotating table of the jig bore and surface c accurately centered and leveled so that the axis of the scattering table and rotating table coincided. The goniometer circle was mounted on top of the table and the circle was carefully leveled and centered. It was essential that the axis of the scattering table and of the circle should coincide. The observation microscope for the goniometer was fixed with respect to the surface table by means of the channel assembly. To avoid the ambiguity arising from the finite width of the graduations, the marks were engraved with a 45° cutter as shown in Fig. 6. The left-hand edge, which is radial, is used for the positioning. The arrangement used permits a good control on the length and depth of the cut. During the graduation process the Bausch and Lomb reading microscope was placed 60° from the cutter in order to monitor the settings of the table. Subsequent tests in which the table was mounted on its spindle housing assembly, show that the table is good to within ± 1 min. of arc everywhere and to 0.5 min. of arc over about 80% of the circumference.

B. Collimator and Its Adjustments

Figure 7A is a cross-sectional drawing of the collimator and Fig. 8 is a photograph of the collimator, the coupling for the beam tube and collimator tube adjustment. The collimator tube is about 37.50 in. long and has an inside diameter of 1.15 in. It is coupled to the 2-in. -diameter beam tube from the cyclotron through a foil holder, the quadrant detector, and the valve which separates the cyclotron vacuum system from the scattering chamber. The purpose of the collimator system is to define the direction, the diameter, and the divergence of the beam. The defining apertures, located at points a and b, are 34.00 in. apart. The diameter of the

Fig. 7A. Collimator tube.

Fig. 7B. Adjustments for collimator tube.

Fig. 8. Collimator assembly.

apertures is determined to some extent by the hot spot obtained when the cyclotron beam is focussed on the first aperture. It usually is desirable to use the collimator to determine the beam direction; and in correcting for the finite diameter of the beam one assumes that the beam density is uniform across the collimator aperture. Therefore, the collimator aperture should not be appreciably larger than the hot spot. On the other hand, if the collimator aperture is made too small it may be impossible to set the system up so as to transmit a beam through it as the transmitted beam may contain an excessive low-energy component because of penetration of the edges of the slit. We have chosen a diameter of 0.124 or 0.125 in. for the collimator aperture. This is somewhat smaller than the best hot spot observed so far at this point. If our hot spot had been 0.5 mm (= 0.020 in.) in diameter, the maximum resulting error in beam direction would have displaced the beam 1.5 mm at the target. This displacement would have resulted in a maximum error in angle of about 8 min. of arc in the forward direction and in an error in $d\omega$ of about 2% at 90° if the defining aperture of the detector had been 15 cm from the center of the scattering table. A number of apertures (c, d, and e) have been installed. The purpose of c and d is to prevent particles scattered by the first aperture and scattered again from the beam tube from being transmitted through the aperture b. Aperture e has been inserted to shield the detector from particles scattered by aperture b. The collimator is lined with seamless tantalum tubing. The disks have a front cover plate of tantalum and the defining apertures have been made of gold to reduce the neutron flux and the fairly long-lived activity induced by bombardment with the deuteron and alpha beams. The end of the beam tube inside the scattering chamber becomes warm while the beam is on. The plug f has been installed for use in testing, as the terminal for the tantalum spacer tubes which keep the disks located, and for gas scattering purposes. The supporting system shown in Fig. 7B provides for the alignment requirements: A gives the vertical motion, B the horizontal motion, D the rotation in the horizontal plane, and

E the rotation in the vertical plane. It should be noted that, because of the long lever arm, the tolerances in the machining of these parts have to be exceedingly close in order to avoid excessive motion near aperture b. Clamps G, which are used to clamp the tube after alignment, eliminate the slight motion due to unavoidable clearances in the adjustment controls. The vacuum seal is again made by means of a sylphon bellows. As an aid in finding the beam, a quadrant detector Q (Fig. 2) is inserted in front of the collimating tube. By use of foil changer H, the beam energy can be reduced slightly by inserting thin foils. Larger reductions in beam energy must be made by introducing foils between the first and the second set of quadrupole focussing magnets. The remotely controlled system for changing these foils has been described elsewhere.²

C. Vacuum Chamber

The chamber is made out of cold-rolled steel, 1.5 in. thick. The walls of the chamber have been suitably reinforced to minimize deflections due to evacuation. The maximum deflection of the top cover, on evacuation, is 0.40 in. The chamber consists of a top plate, a bottom plate, and the ring. The inside diameter of the ring is 60.000 ± 0.015 in. The inside height is 18.000 ± 0.005 in. The O-ring grooves have been machined in the ring with a minimum of clearance. The ring is placed on the bottom plate with the O-ring inserted in the groove.

The bottom plate has a center hole for the table spindle to pass through. It has two 4-in. holes for connection of the vacuum lines. Inserted into each of the 4-in. holes is a piece of steel tubing which is held only by the flange of the vacuum system. This was necessary because in vacuum testing it became apparent that the welds on these two flanges contained rather large holes. Rather than reweld the finished plate and risk distortions, the chamber was sealed by inserting these tubes with an O-ring at each end. Two holes 1.25 in. in diameter are provided for

vacuum gauges and gas inlet systems.

The top plate has a center hole of 12 -in. diameter. Two reference surfaces, concentric with the center bore to 0.005 in. total indicator reading have been provided. Besides, six holes with 6-in. diameter are available in the top plate. These holes are 60° apart and their centers are at a distance of 22 in. from the center of the chamber. The ring has eleven holes 6 in. in diameter located on the center line of the ring. These holes are at 17° , 45° , 75° , 105° , 135° , and 163° to the beam direction on one side of the beam and at 30° , 60° , 90° , 120° , and 150° on the other. Two horizontal locating surfaces are provided, perpendicular to the vector from the scattering center to the center of each hole.

Two holes, each 2.25 in. in diameter, have been located at 75° and 120° to the beam direction, respectively. The holes are located at 6.250 in. below the center line of the ring so that their center lines are 0.250 in. below the surface of the scattering table. The 75° hole is used to attach the Bausch and Lomb reading microscope. The 120° hole is used to view the table graduations with the television camera.

The entrance port for the beam has a 3.25-in. diameter, and the exit port a 4.625-in. diameter. These two holes were line bored with the center line of the borer intersecting the vertical center line within 0.002 in. This provision is essential for the alignment of the equipment.

In replacing the top lid on the chamber, the lid is lowered to about 2 in. above the ring. It is then centered by means of two long bolts and then let down at slow speed.

The chamber is evacuated by two Welch pumps, model 1397-B. The vacuum in normal operation is about 50×10^{-3} mm Hg. The scattering chamber is connected directly to the vacuum system of the cyclotron, in which the pressure cannot be over 8×10^{-6} mm for satisfactory operation. Although a diffusion pump has been provided on the scattering chamber,

it does not need to be used in normal operation.

D. Supporting Framework

Since the cyclotron beam line is about 6.5 ft above the floor of the experimental area, it was necessary to build a substantial supporting framework. From Fig. 1 it is evident that there is not sufficient space between the wall of the cyclotron vault and the collimator of the scattering chamber to permit alignment of the scattering geometry in the actual location of the scattering chamber. Therefore the supporting framework has to provide the necessary motions to make the beam line defined by the collimating system coincide with the beam line from the cyclotron. The framework shown in Fig. 2 consists of four triangular frames M, N, O, and F: The bottom frame M is on casters to provide the horizontal motion; the lower adjusting frame N gives the tilt with respect to the floor of the experimental area; the upper adjusting frame O rotates on N; and the top frame F supports the collimator, the table, and the vacuum chamber.

The bottom frame M is made of 6-in. ship channel. It stands on three 8-in. grooved swivel casters which travel on angle-iron rails bolted to boiler plate. The plate is leveled with shims and fastened to the concrete floor so that the angle-iron tracks are approximately perpendicular to the direction of the cyclotron beam. In order to keep the scattering chamber located along the track, a grooved track lock has been bolted to the bottom frame. Threaded blocks have been mounted at the three corners of frame M. A nut resting on ball bearings mounted in each block is used to give vertical motion of the bolt screwed into each block. Hardened balls mounted on top of the bolts locate the lower adjusting frame with respect to the bottom frame by means of the usual arrangement of three plates: one flat, one with a V-groove, and one with a conical pit. Turning the upper adjusting frame relative to the lower one provides the rotational motion required

in aligning the scattering chamber with respect to the cyclotron beam. Each of these frames is made of 4-in. ship channel with a piece of 16-in. ship channel going through the center of the triangle. A bearing mounted on the 16-in. channel of the upper adjusting frame carries an axle that goes through a similar bearing in the lower adjusting frame to fix the axis of rotation. The upper adjusting frame rests on the lower through three double rows of ball bearings which ride on hardened plates fastened to the lower one. The rotational motion is produced by means of the screw arrangement shown in Fig. 2. A locking arrangement has been provided to lock the system after alignment.

The top frame F rests on the frame O through three columns mounted at the corners of the triangle. The top frame is made of 4-in. ship channel. It supports the vacuum chamber at points immediately above the columns through a system similar to that used to carry the lower adjusting frame on the bottom frame. The spindle assembly of the detector table is carried on three hardened balls on the tips of bolts threaded through the centers of the sides of the triangle. A piece of 6-in. ship channel welded onto this frame forms a rigid horizontal arm on which the beam-collimating system is mounted with aluminum brackets.

E. Collector Cup Assembly

The transmitted beam is collected in a Faraday cup, placed about 30 in. from the scattering chamber so that the radiation due to stopping the beam in it will not produce an excessive background counting rate in the detectors. Figure 9 is a photograph of the collector cup assembly. In order to reduce the neutron flux, the beam is stopped on a gold disk. The i.d. of the cup is 3 in. It is located inside a brass cylinder with an inside diameter of 4 in. and a wall thickness of 0.190 in. The collector cup unit has its own vacuum system and is separated from the main scattering chamber by a 0.002-in. Al foil which is 8 in. from the scattering chamber.

Fig. 9. Collector cup assembly.

Fig. 10. Schematic diagram of collector cup.

A line drawing of the cross section of the collector cup is shown in Fig. 10. The front end of the collector cup is supported by a lucite sleeve a. A number of pump-out holes have been made in the sleeve. A grounded brass shield, b, is press fitted over the lucite sleeve since the omission of either this front-end support or the grounded shield appeared to destroy the reproducibility of the current integration. At the rear the cup is supported through the back plate made of polystyrene to provide a high resistance to ground. This polystyrene plate is also covered with a grounded shield, d. The collector cup is located so that its axis is, to a good approximation, in line with the axis of the collimating system. To keep tolerances in the manufacture of the parts to reasonable values, a sylphon bellows connects the scattering chamber to the collector-cup system. Two of the main extraneous contributions to the integrated current are from secondary electrons and from ionization of the residual gas in the collector cup. The effects due to ionization can be readily observed by varying the potential of the cup relative to its housing or by varying the beam current. While appreciable effects do exist when the pressure is of the order of 3×10^{-2} mm Hg, no observable effects could be detected at the system's normal operating pressure of about 10^{-5} mm Hg. In order to check the effect of secondary electrons from the 0.002 in. Al foil and from the collector cup, a magnet was located near the opening of the Faraday cup. Under our experimental conditions the difference between the integrated current for an average field of 800 gauss and that for no field was less than 0.1%. Under normal operating conditions, the Faraday cup is operated very close to ground potential. The front end of the cup is located about 50 in. from the scattering chamber and subtends an angle of 3.6° . In the case of thin targets, this is sufficient to catch the transmitted beam; but for thick targets the charge measured by the current integrator must be corrected for losses from multiple scattering.

The integrating system used in checking the performance was the one described by Cork et al.³ In normal operation the current is integrated by the system designed by Ramler, Benaroya, and Brookshier.⁴ In the latter system, the collector cup is connected to a vibrating-reed electrometer. A cycling integrator accepts the output of this electrometer and integrates it with an accuracy of 0.25%. The input at the integrator is kept at ground potential ± 1 mv. The over-all accuracy of the combination of electrometer and integrator is better than 1% down to 10^{-11} amp and the range of the combination is 10^{-3} to 10^{-16} amp.

F. Detector Arms

The arms that carry the detector units are designed and constructed to meet the following requirements: (a) the arms should be stable so that they will not warp as they age; (b) the center line of each arm should intersect the axis of rotation of the scattering table; (c) the arms should be movable about that axis and should be readily set at any given angle with respect to the beam direction; and (d) at least one of the arms should have a remotely controlled drive to move it over an angular range of about 90° with respect to the scattering table.

Because of the large range of intensities encountered in many experiments, it frequently becomes necessary to change the solid angle subtended by the detector. This involves changing the radial position r of the detector, or replacing the detector aperture with one of different size, or even replacing one detector unit with another. Such motion or replacement should not change the angular position of the detector aperture by more than 0.5 min of arc. Moreover, the solid angle subtended by the detector can be determined with sufficient accuracy only if the distance r to the scattering center is read to better than 0.5 mm. Obviously therefore, these strips, which are 30 in. long and 2 in. wide, should be very stable since the maximum permissible deviation at a point 15 in. from the center is

Fig. 11. Mounting of detector arms.

Fig. 12. Assembly of detector arms.

only about 0.002 in. Therefore the arms were made of air-hardening tool steel which was annealed after rough machining. Each one is bolted to a ring which is located by the spindle of the table-stem assembly. It is necessary that the arms turn freely and independently, since their angular positions are adjusted by moving them at the edge of the table. Figures 11 and 12 are a detailed diagram and a photograph of the system. The inside diameter of the rings is 0.0002 in. larger than the spindle housing which locates them. The rings are made of hot-rolled steel which was normalized. The bearing surfaces between them are separated by phosphor bronze shims b. A bronze bearing surface c has been placed on top of the highest ring. The system is held in place by means of three Vlier plungers d passing through a special steel nut which, after it was tightened, was locked in place with two set screws.

The width of the arms was 2.000 ± 0.001 in. with the sides parallel to within 0.005 in. (total indicator reading). The thickness of the arms is 0.375 in. The shape is indicated in cross section in Fig. 11. A stainless steel scale is fastened in a recess ground in each arm. This scale, which was located with respect to the axis of rotation with the aid of a Zeiss comparator, reads the distance to the center of the table directly in 0.5-mm steps. The center line of the arm is indicated by a groove at the end to permit one to set the arm at a given division mark on the circumference of the table. After the process described in more detail under "Alignment Procedure" the arms were pinned into place with respect to the rings. The two lower arms are adjusted to have their top surfaces exactly the same distance from the plane of the table. The two middle arms also are at the same height above the table. Blocks i and j have been fastened under the arms so that they are supported on both the middle ring and the outer ring of the scattering table. The position of any arm with respect to the table can be read easily by use of a reference

line which has been cut in the end of the arm (See Fig. 11). This reference mark can be accurately aligned with respect to the graduation of the table by use of the reading microscope. In order to provide the accurate motion required for precise alignment, a gear which travels on the gear rack *g* of the table (cf. part A of this section) is attached to the arm. The reference mark can then be aligned with a given graduation mark on the table by turning the knob and the arm can be clamped to the table by tightening screw *v*. The clamp has been cut out so as to obscure as little of the graduations on the table as possible.

In the design of the scattering chamber it was considered necessary to have one detector arm which could either move with the table or be moved with respect to the table by remote control. Originally it was intended to drive this arm, when moved with respect to the table, by means of a drive shaft in the center of the table spindle (Fig. 5). However, with the addition of a gear rack on the circumference of the table it becomes more practical to drive the arm from the gear rack. This is done in principle by using a motor drive on knob *u* (Fig. 11). The detailed description of the driving system and indicator system is given in Sec. II.

G. The Detector Unit

The detector unit carries the detectors and the defining aperture that determines the angle of scattering and the subtended solid angle. A three-dimensional exploded view of the detector unit is given in Fig. 13 and a side view in Fig. 14. In order to make use of the radial alignment of the detector arms, the unit is located with respect to the arms by runners *r* attached to the base of the detector units as shown in Fig. 15. The front end can then be set at any given graduation on the arm scale. The defining aperture *c* is made of gold and is machined so that the opening and the circumference are concentric. The aperture has a 2° taper to minimize effects due to penetrations of the slit edge and its diameter is measured

Fig. 13. Detector unit.

Fig. 14. Detector unit.

Fig. 15. Photograph of detector unit.

on the Zeiss comparator. The o.d. of the aperture is held to within 0.002 in. of that of the opening in block b. Block b is made of Fansteel 77 and provides shielding for the detectors. If one wishes the angle of scattering to be determined by the position of the detector arm regardless of the position of the detector unit on the arm, it is necessary that when the arm is set at 0° the defining aperture should be in line with the apertures of the beam-collimating system at both small and large values of the distance to the center of scattering. This requires that the block b be correctly centered between the runners and be adjusted to the proper height above the arm.

At the particle energies obtained from the 60-in. cyclotron, a great number of reactions occur. Hence, except in some very special cases, it is necessary to identify the particle emitted from the target. This is done through the use of two detectors, a thin one subsequently referred to as the dE/dx detector and a thicker one, subsequently referred to as the E detector. The product of the signals from the two detectors is proportional to MZ^2 to a good approximation. However, when a wide range of energies is accepted by the detector system, the product $E(dE/dx)$ does not provide a satisfactory separation of different nuclei and it becomes necessary to use the product $(dE/dx) (E + k dE/dx + \lambda E_0)$, where E_0 is a constant and k and λ are adjustable parameters. In order to determine the proper value of the parameters for a given experimental arrangement, it is necessary to calibrate the detectors by use of a beam of known particles with a variable energy. To vary the energy the detector unit also contains three disks by means of which from 0 to 0.150 in. of absorber can be inserted in steps of 0.001 in. The absorber wheels are made of aluminum and have a thickness of 0.125 in. They are mounted between block b and a piece of Fansteel 77 metal d, 0.250 in. thick, as shown in Fig. 14. A gear rack f is mounted on the outside circumference of the disks which can be driven by gears g, one of which is shown in Fig. 13.

The disks are mounted on ball bearings and separated from each other and blocks b and d by washers 0.0156 in. thick. The foils are placed in the holes h and held in place by springs made of phosphor bronze. They are mounted so that the heavier foils are close to the block d to reduce losses from multiple scattering in thick absorbers.

H. The Target Foil Changer

In the course of operation it became obvious that in many instances it was necessary to compare the results from different targets, all other things remaining equal. Furthermore it was desirable to run the cyclotron without interruption as explained in the introduction. The target changer permits the insertion of eight different targets in the scattering chamber. The target holders (Fig. 16) were designed to keep the target foils taut without stretching them when changed. The front face has been machined at an angle to avoid interference of the holders with the scattered beam. Occasionally when only a small amount of target material is available (e.g., in foils of Fe^{57} or Ni^{61}), an insert which permitted the use of a foil of small diameter was used in the holder. The target holders are fastened on the disk by two screws. For removal, one of these is released a little and the other removed so that targets can be changed rapidly without excessive exposure to high radiation levels. A photograph of the target changer is shown in Fig. 17, an exploded view in Fig. 18, and the front elevation in Fig. 19. To maintain the desired accuracy of operation, it is necessary that the target be on the axis of rotation of the scattering chamber. It is also necessary that the angle of the target with respect to the beam direction be known accurately. When the normal to the target is at 45° to the beam, an error in angle of 18 min produces an error in the target thickness of 0.5%. To keep the error to about 0.1%, the orientation of the target must be known to ± 3 min of arc. At an angle of 60° , the required accuracies become 6 min and 2 min of arc,

Fig. 16. Target holders.

Fig. 17. Photograph of target changer.

Fig. 18. Target-changer assembly.

Fig. 19. Target changer.

respectively. While the thickness of the target foil usually is a more uncertain quantity, the latter can be averaged out by using a number of different foils or by using different areas of the same foil. The orientation of the target is, however, more likely to contain a systematic error.

The disk A carrying the targets is supported by a bracket B which has a hole with sufficient clearance to avoid interference with scattered particles. This support has been machined so that it is perpendicular to the table of the foil changer and has been pinned in position during assembly. The disk A has a block C with two ball bearings (Fig. 19) screwed onto it. The block D is fastened to the top of the support bracket. The brass table is supported by two sets of ball bearings E resting on the base which in turn is supported by the graduated table of the scattering chamber. The target changer itself can then be kept fixed with respect to the vacuum can of the scattering chamber by means of the brake shown in Fig. 18. However this obviously will not work unless the ball bearings which support the table T are perfectly centered. In order to achieve the centering, use was made of the protruding end of the axis of rotation of the table stem assembly. It is possible to lock the table T to the scattering table by means of the lock screw shown in Fig. 18. If the brake shoe is retracted the target changer will rotate with the table. One can set the target changer by setting up a transit at 60° to the beam direction. The target changer is then set so that the foil holder is in line with the transit. The target changer is then locked to the scattering table and the scattering table rotated through the predetermined angle, usually 15° . The table brake is applied, the brake of the target changer is applied, and the lock screw loosened. Under this system the location of the target with respect to the beam direction is as accurate as the table graduations together with the accuracy of the determination of the 60° direction of the transit. In general an accuracy of ± 3 min can be

fairly readily obtained. The description of the indexing and control of the target changer is given in Sec. II.

I. Alignment of the Scattering Chamber

The alignment of the scattering chamber consists of two phases. In the first place the scattering chamber has to be adjusted so that the center of scattering is on the axis of rotation of the scattering table and the direction defined by the collimating system apertures is parallel to the table. In the second phase the direction defined by the collimating system is made to coincide with the direction of the cyclotron beam without disturbing the alignment made in the first phase. The first phase will be referred to as alignment of the scattering system, the second as the alignment of the beam direction.

1. Alignment of Scattering System

One wants the beam direction as defined by the apertures in the beam collimating system to intersect the axis of rotation of the table and to be perpendicular to it. It also is desirable to have the beam direction pass approximately through the center of the port of the collector cup. The adjusting procedure is as follows: The support frame and the vacuum can are leveled by means of the adjustments provided for this purpose. The scattering table is centered approximately with respect to the vacuum chamber by means of indicators. The pads which locate the table stem assembly are pinned after the table has been centered. The table was intended to have its surface 6.000 in. below the center line of the exit ports, but in practice it was not quite possible to achieve this distance. The transit is set up at the cyclotron end of the collimating tube and is leveled. It is adjusted to look through the collimator along the line determined by the axis of rotation of the scattering table and the center of the exit port to the collector cup. The location of the axis of rotation is determined by placing a positioning mark on the table and rotating the

table through 180° . Positions at 60° and 120° are used to average out the inaccuracy present in the table graduations. As pointed out previously, the use of only one set of positions would result in an error in the location of the table axis of not more than 0.004 in. Therefore one can obtain an error of 0.002 in. by merely disregarding the worst of the three sets. Once the direction of the transit is determined, one can use the adjustments on the collimator tube to bring the defining slit system of the collimator tube in line with the transit direction. After this has been done the collimator tube is clamped down.

It is also necessary to pin the detector arms in place after they have been set up so that their center lines are radial. If a block which has the same width as the arms is placed on an arm and is marked with a center line, this arm can be rotated until the line coincides with the cross hairs of the transit. If one moves the block along the arm, the center line of the block should remain in coincidence with the cross hairs. The arm can be adjusted until the center line of the block is in coincidence with the cross hair regardless of the block's position on the arm. After the arms have been pinned in position, the necessary parameters for the detector units have to be determined. This is achieved by using a detector unit which has adjustments perpendicular to the arm. A sketch of the base of the detector unit is shown in Fig. 20. Vertical motion is provided by screw A and

Fig. 20. Adjustments for detector unit.

Fig. 21. Microscope mounting.

horizontal motion by B. The adjustment screws are adjusted until the aperture in block b of the detector unit (Fig. 13) is in line with the transit direction. These dimensions are then used in the construction of the four other detectors which contain no further adjustments. The face of the defining aperture should be perpendicular to the vector from the center of scattering. This can be readily achieved once the arms are radial. In order to establish a reference angle, one of the arms was set at the 0° position on the scattering table. The table was then rotated so that the aperture in the detector unit was in line with the transit direction. The reading microscope which is attached to the can as shown in Fig. 21 is then adjusted to read 75° .

2. Alignment of the Beam Direction

To determine the direction of the focused beam from the cyclotron, a tube 24 in. long was placed in the cyclotron beam tube and the 0.001-in. Al foils mounted at its ends and at its center were irradiated. Radiographs of the activity induced in the aluminum were taken to determine the beam direction. The transit was set up so that it sighted along the axis of this beam. The height adjustments on the bottom frame, the rotating system determined by the two frames above it, and the position of the chamber along the tracks were then adjusted until the beam-collimating system was in line with the transit direction. The collector cup was then placed in position and coupled to the scattering chamber.

3. Accuracy of the Scattering Chamber

As far as the chamber is concerned, the accuracy of the measured differential cross sections is determined by the accuracy of determination of the following factors:

1. Subtended solid angle of the detecting aperture. The error is usually less than 0.2%.
2. The angle of scattering, read directly to $\pm 0.5\%$.

3. The target angle, usually known to $\pm 0.5\%$.
4. The accuracy of the current integration which is certainly good to 1% and with some care can be measured to $\pm 0.5\%$.

II. DETECTION AND REMOTE CONTROL

A. Detection

In the present experimental program the detection has been done so far mostly by NaI(Tl) crystals. In experimental work with 43-Mev alpha particles and 21.6-Mev deuterons, there are a great many reaction products. To distinguish between the different reaction products, a combination of two detectors is used. The first is a thin counter to measure the rate of energy loss dE/dx , the second is a thick one to measure the energy E . The product of the signals from these two detectors is proportional to MZ^2 . The usual choice as dE/dx detector has been the proportional counter. It can be rather thin and still give excellent energy resolution and therefore good particle resolution. On the other hand, the proportional counter requires rather high voltages which in turn require a better vacuum than usually attained in our chamber, and it has a longer dead time than the NaI(Tl) scintillation counter. Therefore we use a NaI(Tl) crystal as the dE/dx detector. This permits a satisfactory particle identification and satisfactory counting speed.

In some cases it is feasible to use a single crystal as the detector. [In the case of elastic scattering of deuterons by nuclei, this can be done successfully at small angles (less than 40°) by making the crystal just slightly thicker than the range of the elastically scattered deuterons.] However, in most cases it is necessary to use a double-crystal setup. The sandwich is made by cementing a NaI(Tl) crystal on a quartz plate and machining it down, in a room with controlled humidity, to the desired thickness. This thickness in our particular case varied from 0.300 in. to 0.030 in. depending upon the experiment. This E crystal is then covered

with a 0.0004-in. foil of Al. The second (dE/dx) crystal is cemented to the Al foil and machined down to its desired thickness. The thickness of the dE/dx crystal has varied from 0.020 to 0.003 in. It is of course essential that the thickness of a given dE/dx crystal be uniform. The light from the dE/dx crystal is collected by means of an air light pipe. The quartz plate with the two crystals mounted on it is mounted in a box as shown in Fig. 22.

Fig. 22. Schematic drawing of crystal box.

A section of the box is shown in Fig. 13, where the crystal n is shown cemented to the quartz plate q . The photomultiplier PM 1 looks at the E crystal and photomultiplier PM 2 looks at the dE/dx crystal obliquely through window c of Fig. 22. The box is filled with dry air and is closed by its front window d (Fig. 22) made of 0.00025-in. permalloy foil. The inside of the box is coated with alumina in sodium silicate binder. The quartz plates q and c are seated on O-ring seals as is the entrance window d . Under these conditions the crystal did not deteriorate over periods of several months. The cathode followers CF1 and CF2, whose circuit diagram is given in Fig. 23, are mounted on the photomultipliers as shown in Fig. 13. The signal cables are brought out

Fig. 23. Schematic drawing of preamplifier.

through one of the ports in the vacuum chamber through a connector assembly shown in Fig. 17 (see part F of this section). The signals are transmitted to the amplifier in the counting room 150 ft. away. After amplification the signals are multiplied electronically. Two multiplier circuits have been built. The one whose circuit diagram is given in Fig. 24 is a modification by Roddick⁵ of the multiplier described by Stokes.⁶ A special amplifier to amplify the output of the unit is shown in Fig. 25. The other multiplier circuit is basically the one described by Aschenbrenner.⁷ Its circuit diagram is given in Fig. 26. Of course the output of a multiplier, which gives the product of dE/dx and E , is not strictly proportional to MZ^2 . Since the dE/dx crystal cannot be of infinitesimal thickness, the product pulse proportional to $\Delta E \cdot E$,

Fig. 24. Circuit diagram of pulse multiplier.

Fig. 27. Circuit diagram of dual adder.

Fig. 28. Block diagram of detector.

the output spectrum of the pulse multiplier remains the same regardless of the incident energy of the particle. Then the multichannel analyzer is gated by the output of the differential discriminator, whose upper and lower level are adjusted for the desired kind of particles. With the gate thus fixed, the E signal is fed into the multichannel analyzer. The energy calibration of the spectrum obtained from the multichannel analyzer is of course not linear with the energy of the particles emitted from the target since the dE/dx crystal, permalloy window, Al foil, and air are equivalent to a fixed absorber thickness which has to be determined. It is assumed that the energy of the particles from the cyclotron is known, although it is true that this initial energy is subject to fluctuations due to the machine parameters. It is quite feasible for the initial energy to vary approximately 2% in response to changes in these parameters. However, once the machine has been operating with a given set of parameters for 30 min, its energy will remain constant to better than 0.5%, provided that there are no serious fluctuations in the temperature of the cooling water for the magnet. It is also assumed that the range-energy curves for protons, deuterons, and alpha particles are accurately known and that the response of the E detection system is proportional to the energy dissipated in the E crystal. The system of absorber wheels is then used to insert,

gradually, known amounts of Al absorber in front of the detection unit until no signal from the E detector is seen. The total amount of absorber needed to eliminate the signal from the E detector plus the unknown absorber in front of the E crystal should be equal to the known range of the particles. From this one can calculate the energies dissipated in the crystal for each of the various amounts of absorber. The resulting graph of channel number vs energy can then again be corrected by the few mg/cm^2 necessary to obtain a consistent picture. With the amount of absorber known, the energies of particles resulting from reaction products can be obtained. In some cases, such as (α, t) reactions, the range of the product particle is considerably larger than the range of the incident particle and by placing some Al absorber ahead of the dE/dx detector, it is possible to eliminate the initial particle from either the E detector or both E and dE/dx detectors. This permits the detection of the reaction product in the presence of the elastically scattered incident particles, with a satisfactory counting rate even at small angles. Because of the nonlinearity of the range-energy relation, the insertion of additional absorber can be used to good advantage to improve the resolution of the system. It has been used to separate the deuterons inelastically scattered from the 1.04-Mev 2^+ level in Zn^{64} from the elastically scattered deuterons in the forward direction. When a great amount of absorber is used, a correction for multiple scattering is necessary when one attempts to determine absolute cross sections. This is especially true if the detecting crystals are not very close to the absorber wheels. One must be careful to take into account the fact that the loss due to multiple scattering is energy dependent. In general, the loss due to the total reaction cross section in the absorber foils can be neglected.

B. Remote Control of the Detector Unit

The motors that drive the absorber wheels are mounted on the base of the detector assembly under the E photomultiplier tube as shown in Fig. 29

Fig. 29. View of detector unit, showing the location of the motors and the crystal box.

Fig. 30. Circuit diagram for the absorber wheel in front of the detector.

Dc motors could not be used because of the problem introduced by arcing at the brushes. The motors used are small reversible ac motors, 1 in. in diameter by 3 in. long, made by Globe Industries, Dayton, Ohio.

The absorber wheels are 3 in. in diameter and 0.125 in. thick. The spacing between the wheels is 0.0156 in. A ring gear is mounted along the circumference of each wheel. The wheel is then directly driven by the motor, thus preventing any backlash which might occur in a gear rack or mechanical linkage.

Each wheel is set accurately at any one of six different positions. A limit switch L shown in Fig. 13, rides on a gear-driven cam k that makes six revolutions for each revolution of the wheel. The cam is so designed that when the wheel reaches the desired position, the switch actuator falls into an indentation and opens the motor circuit. The large gear reducer absorbs all overtravel so that the motor stops with the absorber foil within 0.005 in. of its proper position.

The diagram of the control circuit is shown in Fig. 30. The limit switch of a given wheel actuates a double-pole, double-throw relay which in turn energizes a latching relay, thereby opening the motor circuit for that wheel. Simultaneously the rotary stepping switch, corresponding to that motor, is actuated so that it advances one position. Panel lights indicate the position of the rotary stepping switch and hence the position of the wheel. A selector switch on the control panel permits the operator to select the motor and the corresponding rotary stepping switch to be actuated.

C. Remote Control of the Movable Arm

The movable arm is provided with a remotely controlled drive and an indicating system so the detector angle can be changed with respect to the scattering table. Its range of approximately 80° is limited by the legs of the target changer, which are bolted to the scattering table at a

Fig. 31. Movable arm.

distance of about 12 in. from the center of the chamber. The mechanical arrangement is shown in Fig. 31.

The drive motor, a Helipot precision potentiometer *b*, and corresponding gears are mounted on a plate *E* which is clamped to the arm. A gear *c* on the arm engages with the rack *e* on the scattering table. Another gear, of the same pitch diameter, on the shaft of gear *c* engages with the gear of the drive motor. The remote-control unit can be removed from the arm easily and quickly for adjustment or repair. The plate *E* on which the unit is mounted is held on the arm by two bolts fastened to a $\frac{1}{4}$ -in. Al strip. This strip *d* passes under the arm. To maintain proper elevation and alignment, spacers have been installed on the base of the plate *E* and rest on the arm.

The drive gear has a pitch diameter of $\frac{1}{4}$ -in. and the Helipot gear has a pitch diameter of $1\frac{1}{2}$ in. so that the gear ratio is 6:1. Six revolutions of the drive gear correspond to moving the arm approximately 9° . When a 10-turn Helipot is used, the system has a range of approximately 90° .

The electronic control is shown in Fig. 32. It consists basically of a bridge circuit with two Helipots. Each potentiometer is connected to the grid of one triode of a 6SL7 tube. One Helipot is panel mounted while the other is geared to the drive motor on the movable arm, as shown in Fig. 31. A relay is used as the plate load resistor in each half of the 6SN7. The SPDT contacts of the relays are connected to either side of the reversible motor and to null indicator lights Ne51 on the control panel. Varying the control Helipot unbalances the circuit so that one relay closes and drives the motor until the slave Helipot balances the bridge. When the bridge has been balanced, the relay opens the motor circuit and closes the null indicator light circuit to indicate that the bridge is in balance and the arm is at the angle indicated by the master Helipot.

Fig. 32. Circuit diagram of remote control for movable arm.

D. Remote Control of the Target Changer

The target changer consists of a target-holding wheel A, a reversible drive motor b and a bank of miniature switches. The mechanical arrangement is shown in Fig. 18. The wheel is driven by a Geneva type drive with the drive disk on the shaft of a 115-v ac reversible motor. The corresponding drive grooves are machined on the target-holding wheel as shown in more detail in Fig. 33. One revolution of the 3-rpm motor turns the wheel through 45° to change from one target to the next.

To position the wheel, a miniature switch s is actuated by a lobe on the Geneva drive disk. When the miniature switch is actuated, the motor drive circuit opens. Any overtravel which may occur in the drive motor will be absorbed in the Geneva drive and not transferred to the wheel.

To indicate which of the eight target positions is in position, a bank of miniature switches is used. The switches, which are used in a binary system, are actuated by cams on the target-holding wheel. The switches are connected to indicating lights on the control panel, the position of the target-holding wheel being indicated by the combination of indicating lights turned on. The electrical circuit used is shown in Fig. 34.

The target changer is held at a given position with respect to the incident beam by means of a brake. The target brake can be released either manually or through a solenoid actuator. The solenoid actuator is energized by 110 v ac through a toggle switch at the target-changer panel. When the brake is released manually or with the solenoid actuator, the changer is free to rotate with the scattering table.

E. Remote Control of Scattering Table

The remote control system for the scattering table incorporates a reversible drive motor, a safety slip clutch, and a closed-circuit television system. The complete system generally is accurate to within

Fig. 33. Geneva drive for target changer.

Fig. 34. Circuit diagram of remote control for target changer.

2 min of arc. The electrical circuit used for driving the table is shown in Fig. 35. The table is rotated by a 115-v ac 60-cycle reversible motor

Fig. 35. Circuit diagram for scattering-table drive.

energized by the parallel connection of a single-pole double-throw switch and a spring-loaded switch of the same type. The spring-loaded switch provides a very sensitive means of positioning the table while the SPDT switch can be used to rotate the table through large angles, thereby freeing the operator to direct his attention to some other phase of the experiment.

The slip clutch shown in Fig. 36 has a cast iron disk *d* encased in a brass housing. The brass housing is coupled to the output shaft of a gear reducer *e*. The cast iron disk is coupled to the shaft *h* of the drive gear for the scattering table. Adjusting screws *s* force the cast iron disk into a taper machined in the brass housing. The adjusting screws regulate the pressure exerted by the disk on the housing. When the table is rotated by hand, this clutch slips so the gear reducer does not need to be driven in reverse.

There is a hand crank on the input shaft of the gear reducer to provide manual positioning of the table. The remote-control drive motor is mounted on a hinge bracket along the shaft of the hand crank and engages with a gear on that shaft. The motor can be moved away by use of

Fig. 36. Clutch and gear reducer for table drive.

the hinge bracket to provide manual control.

The closed-circuit television system used (made by General Precision Laboratories, Pleasantville, N.Y.) provides a direct-reading indicating system. The TV camera looks in at the graduations on the edge of the table through a lucite port in the wall of the scattering chamber. By use of a 1-in. lens and a $\frac{1}{4}$ -in. spacer ring, the numbers on the graduated table, which are approximately $\frac{1}{16}$ -in. high, are magnified to approximately 5 times their size.

The graduated edge of the table is illuminated by an inspector's lamp which is clamped to the wall of the scattering chamber and bent over so that it hangs above the camera lens and shines down at the table edge. This keeps the scattering table between the lamp and the detector units at all angles. Therefore the light from the lamp is not seen by the photo-multiplier systems. A certain amount of drift in the image on the 17-in. monitor does occur. However, such a drift can be readily detected. The table position as observed on the monitor was checked periodically against the position obtained from the reading microscope to eliminate such drifts as may occur during the relatively short time the table is driven during an experiment.

F. Electrical Connections

The electrical cables are brought into the scattering chamber through hermetically sealed connectors. The connectors are mounted on the cover plates of the ports in the chamber wall. The connectors are arranged as shown in Fig. 37. Two types of connectors are used. Coaxial type 82 provides the signal and high-voltage connections, while control cables, B^+ , and filament voltages use AN-type connectors. The coaxial connectors are bulkhead feedthrough adapters. The hermetically sealed AN connectors are flanged receptacles and require adapters in order to

Fig. 37. Connector plate for coaxial cable.

disconnect cables inside the chamber. They are adapted simply by mounting standard AN connectors on a bracket directly behind the sealed connectors and connecting them with pig tails.

The hermetic and standard AN connectors are identical in size, contact number, and contact arrangement. The hermetic connectors used are a 17-contact connector and a 4-contact connector. The 17 contacts are adequate for the necessary control cables and the 4 contacts provide the B^+ and filament voltage for the preamplifiers.

The coaxial feedthrough adapters were designed for high-pressure use and not for vacuum. Some difficulty was encountered in attempting to provide a high-vacuum seal between the outer case of the connector and the cover plate. The outside flange of the connector was machined flat and an O-ring groove was machined around the hole for the feedthrough connector. The connector flange is pulled down against the O ring by screwing the lock-nut tightly against the back of the plate. A good vacuum seal is obtained.

A mounting ring was made to mount the hermetic AN connector on the cover plate for the port. The ring slips over the connector and rests on the connector flange. In order to provide a good vacuum seal, a very shallow groove was cut on the bottom of the connector flange. The flange was set on an O ring. The O-ring groove was machined into the plate around the hole for the AN connector. Three holes were tapped into the plate. The bolts holding the mounting ring are screwed into the tapped holes to pull the connector against the O ring.

III. EXPERIMENTAL RESULTS

The scattering chamber has been used for a number of experiments on elastic and inelastic scattering, measurements of angular distributions of pickup and stripping reactions, and for angular correlation experiments.

The necessity of making observations at small angles with energies such as the ones obtained at the 60-in. cyclotron can be illustrated by the results on the elastic scattering of 43-Mev alpha particles by Ag. The experimental results are shown in Fig. 38. The solid curve was taken from a paper by Cheston and Glassgold.⁹ The potential used was $V(r) = Vf(r) + iWg(r) + V_c$ with

$$f(r) = g(r) = \left\{ 1 + \exp [(r-R)/a] \right\}^{-1}.$$

The parameters of the curve shown were $V = -50$ Mev, $W = -20$ Mev, $R = 7.5$ f, $a = 0.6$ f. The experimental errors have been indicated whenever they were larger than the size of the points. It is obvious that if one had assumed that at about 20° the elastic scattering was Rutherford scattering a rather substantial error would have been made.

In the case of (α, t) reactions on nuclei near $Z = 28$, the main difference between angular distributions corresponding to $\ell = 1$ transitions and those corresponding to $\ell = 3$ transitions occurs at angles between 13° and 15° . It is therefore necessary to make the measurements over this angular range with a small subtended angle. Representative curves are shown in Fig. 39.

In the case of (d, t) reactions and (d, He^3) reactions, the main difference between $\ell = 1$ and $\ell = 3$ transitions similarly occurs at angles less than 15° . Therefore, in order to make estimates of admixtures in a given transition, accurate absolute cross-section measurements at small

Fig. 38. The ratio of measured differential cross sections to Coulomb cross sections for Ag. The errors are smaller than the points, unless shown. The curve was taken from the paper by W. B. Cheston and A. E. Glassgold, Phys. Rev. 106, 1216 (1957).

Fig. 39. Angular distributions for the (α, t) reactions on Y^{89} , Fe^{56} , and Mn^{55} . The $Y^{89}(\alpha, t) Zr^{90}$ ground-state transition is typical for the $\ell = 1$ angular distribution. The two others are typical $\ell = 3$ angular distributions.

angles are necessary. For the theoretical interpretation of the data, reliable values for the cross section at angles as small as 8° are necessary.

The target changer has been used in the comparison of the elastic scattering of 21.6-Mev deuterons by separated isotopes from Cu^{63} , Cu^{65} , Ni^{58} , and Ni^{60} . The experimental results are shown in Fig. 40. It is obvious that the isotope shift in the diffraction pattern at small angles is too small (about 0.05°) to be measured unless the detector is left unmoved for both isotopes. The experimental procedure employed was to obtain the cross section at any given angle for all four targets in succession so that a given laboratory angle was identical for all four targets. The analysis is shown in Fig. 41. It is obvious that rather significant shifts in the diffraction pattern do occur, even at small angles.

Fig. 40. Angular distributions for the elastic scattering of 21.6-Mev deuterons by Ni^{58} , Ni^{60} , Cu^{63} , and Cu^{65} . The data have been multiplied by $\sin^4(\theta/2)$ and normalized with respect to each other at forward angles. The statistical errors are less than 2% at angles smaller than 80 degrees and less than 4% in others.

Fig. 41. Angular distributions of $\sigma_1/\sigma_{R1} - \sigma_2/\sigma_{R2}$ for $\text{Cu}^{63} - \text{Cu}^{65}$, $\text{Ni}^{60} - \text{Cu}^{63}$, and $\text{Ni}^{58} - \text{Ni}^{60}$. The errors shown are the standard deviations derived from the number of counts in the elastic peaks.

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