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MEASUREMENT OF ANGULAR DISTRIBUTIONS OF NUCLEAR REACTION PRODUCTS WITH AN INTERNAL CYCLOTRON BEAM

Bernard L. Cohen
Rodger V. Neidigh

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Bernard L. Cohen
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ELECTROMAGNETIC RESEARCH DIVISION
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Date Issued

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ABSTRACT

Angular distributions of elastically scattered protons, and of deuterons and tritons from (p,d) and (p,t) reactions are being measured with the internal 22 Mev proton beam of the ORNL 86-inch cyclotron. The particles are detected by observing the activities induced by them-- Cu(p,n) $\longrightarrow$ 38 minutes for protons, Pb(d,p) $\longrightarrow$ 3.3 hours for deuterons, and Co(t,p) $\longrightarrow$ 1.6 hours for tritons. Energy discrimination is obtained by absorbers. The energy and energy distribution of the incident beam are found by measuring the excitation function for Cu(p,n) and comparing with published data. Angles are determined (within 1/2°) by beam-locating experiments, and checked by the Rutherford absolute cross section and $\csc^4 \theta/2$ law for elastic scattering from heavy elements at small angles. The current is monitored by neutron counters, and measured by counting the activity in the target after bombardment. This is calibrated in a separate run against the published Cu(p,n) cross section. The target is cooled by radiation only. The background is reduced by various types of carbon shielding. The solutions of other difficulties are described and sample results are shown. The extension of these methods to the measurement of alpha, neutron and high energy gamma ray angular distributions is discussed.

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INTRODUCTION

Since the Oak Ridge National Laboratory 86-inch cyclotron was originally constructed without provision for beam deflection and was strongly committed to other work, the nuclear physics research program was of necessity limited to experiments using the internal circulating beam and requiring a minimum of cyclotron bombarding time. Among the most successful experiments of this type that have been developed is the measurement of the angular distributions of deuterons, tritons, and high energy protons from (p,d), (p,t), and (p,p) (elastic) reactions in various target elements. It is the purpose of this paper to describe the methods of performing these measurements. The detailed results of the separate experiments will be reported separately.

Section I of this report includes a discussion of the various problems encountered in working out the method and the way in which they were resolved. These include: (a) the development of detection methods, (b) intensity consideration, (c) the monitoring and measurement of the cyclotron current, (d) the determination of the angle and angular homogeneity of the incident beam, (e) the elimination of background, and (f) miscellaneous other problems. The measurement of the energy and energy distribution of the incident protons has been discussed in a separate report.[1]

In Section II the design of the target and methods of performing the measurements are described. A few sample results and a discussion of other possible applications are presented in Section III.

1. Cohen, B. L., Measurement of Beam Energy and Energy Distribution on an Internal Cyclotron Target, ORNL-1347, July 1952.

I: EXPERIMENTAL PROBLEMS

Particle Detection

It was obvious from the very first that geometry, time, and background considerations would make the use of counters for particle detection extremely difficult. As an alternative, a method of activation detection was developed which is based on an extension of the threshold detector method commonly used for neutron detection. It consists of exposing a material to the particles to be detected and then determining the activity induced in it by nuclear reactions that can be initiated only by the particle in question. For example, deuterons, can be detected by determining the activity produced by any (d,p) or (d,n) reaction. If they are to be detected in a background of other particles, the material chosen must be such that none of the other particles present can produce this activity or any other activity of comparable half life in the detecting material or any of its impurities. In practice, each case requires specialized techniques, so that perhaps the most suitable way to proceed is to describe the details of the methods used.

Deuteron Detection. The most suitable deuteron detector was found to be lead foil in which deuterons can be detected by the 3.3-hour activity of Pb 209 produced by the reaction Pb 208(d,p)Pb 209. The Pb 209 activity can also be induced by slow neutrons from the reaction Pb 208(n,γ)Pb 209. However, this particular reaction has a very low cross section and in most cases is of minor importance. The fraction of the activity produced by the (n,γ) reaction can be determined by bombarding through an absorber thick enough to remove the deuterons; this fraction may then be subtracted. A search of the isotope tables reveals that no activity of the order of 3.3 hours can be produced by

protons (that is, by (p,n), (p,2n), (p,3n), (p,pn), (p,α), (p,αn), (p,p2n), etc. reactions), alphas, fast neutrons, or any of the other particles that might be emitted from nuclear reactions with appreciable probability. Since the ratio of deuterons to protons is very low in most experiments in a proton cyclotron, special care must be taken to eliminate impurities.

Another complication resulting from the low deuteron-to-proton ratio is that the 12-hour activities of Bi 203 and Bi 204 produced by (p,n) and (p,2n) reactions on Pb 204 give a high counting rate (even though they decay without β emission and Pb 204 is a 1% isotope). In order that the 12-hour activities may be subtracted with sufficient accuracy to give a quantitative determination of the 3.3-hour activity, the samples must be counted for several days. Rather than tie up the counting equipment, it was found expedient to remove the bismuth by radiochemical techniques. This has the added advantage of eliminating activities that are produced by protons on the impurities in the lead.

One very basic limitation to the method of activation detection is that it does not discriminate between particles of different energies. Measurements detect particles of all energies with different efficiencies, and are thus somewhat difficult to analyze theoretically. In many cases, sufficient absorber thickness may be placed over the detectors so that only the longest range deuterons (that is, those which are emitted in reactions leaving the residual nucleus in its ground state) may be detected. Actually, this requires a knowledge of the excitation function for the (d,p) reaction in lead. Since this is not available, the excitation function for the (d,p) reaction in bismuth* was accepted as a suitable approximation. In measuring angular distributions from targets of light elements, center-of-mass corrections are such

---

* Kelly, E. L. and Segre, E., Phys Rev 75, 999 (1949).

that the energy of the deuterons varies considerably with angle. This difficulty may be overcome by setting the absorber thickness at each angle so that the energy of the deuterons striking the lead is the same at each angle. As an example, Curves A and B of Figure 1 show the energy as a function of angle of deuterons emitted from the reaction Be 9(p,d)Be 8 in which the residual nucleus is left in the ground state and the first excited state respectively. The incident proton energy assumed in this experiment is 21 Mev. Curve C shows the thickness of copper absorber necessary to reduce the energy of the ground state group to 10 Mev; and Curve D shows the energy to which the excited state group is reduced. From the excitation function, one sees that the excited state group is detected with very low efficiency. Absorbers were made from weighed copper foils and held together with scotch tape. The thickness changed every 8 1/2 degrees, being adjusted to the proper thickness within 1 mg/cm^2.

Triton Detection. Tritons are detected by the 1.6-hour activity of Co 61 induced by Co 59(t,p)Co 61. The foil is produced by electroplating from cobalt chloride-boric acid solution onto a stainless steel plate, and peeling*. When a cathode of pure cobalt is used, the impurities are held down to approximately 0.1% each of iron, nickel, and copper, and considerably less of all other elements.

After the bombardment, the foils are processed by radiochemical techniques to remove activities from impurities and from the end products of the (n,α) and $(\alpha,2n)$ reactions on cobalt--2.6-hour Mn 56 and 3.0-hour Cu 61 respectively. The samples are then counted under end window Geiger counters with 70 mg/cm^2 absorbers interposed to eliminate the 9-hour internal conversion activity of Co 58 from Co 59(p,pn)Co 58.

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* Sisman, O. et. al., ORNL-299.

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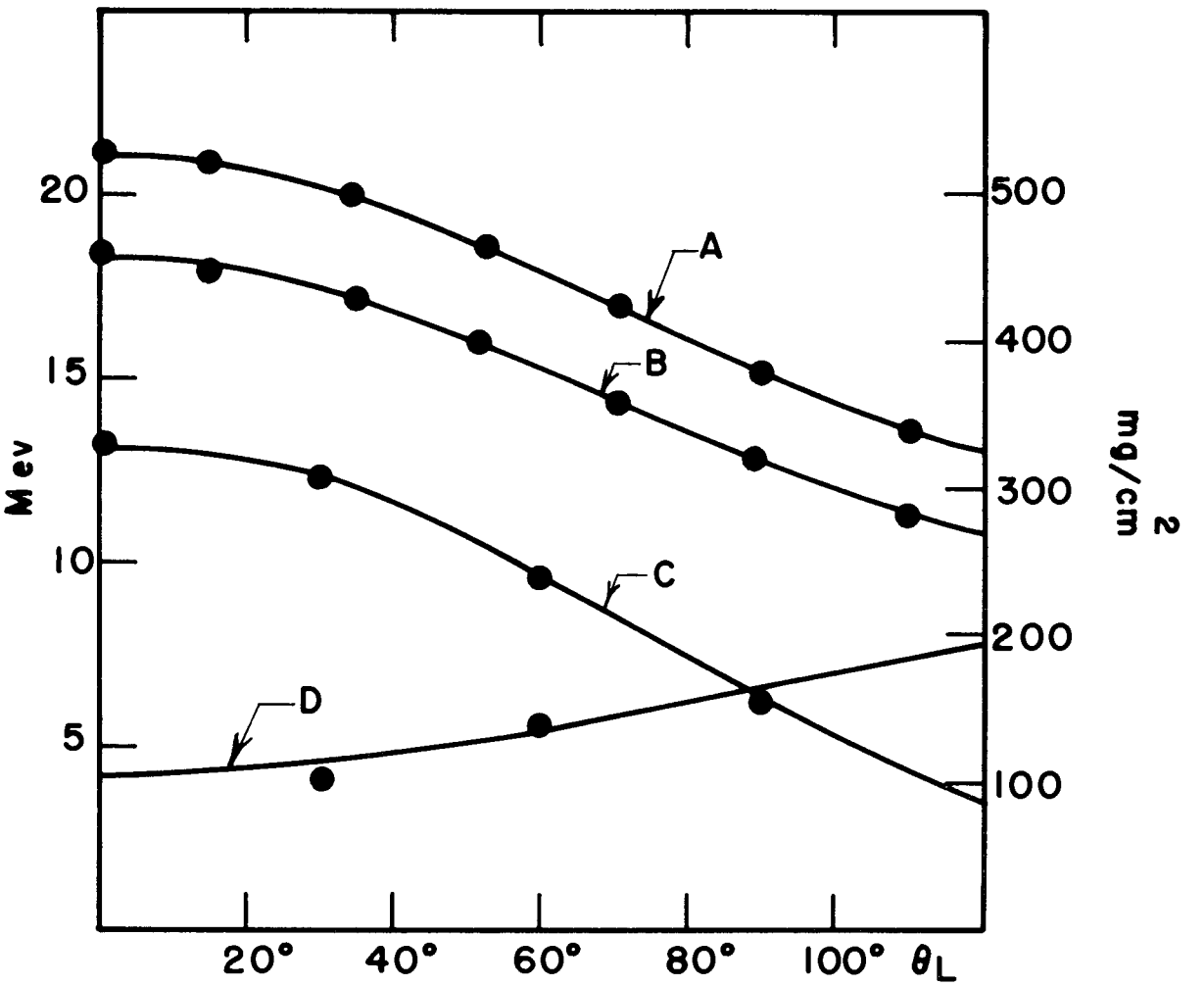

FIGURE 1. CENTER-OF-MASS CORRECTIONS FOR THE REACTIONS
(1) Be 9(p,d)Be 8
(2) Be 9(p,d)Be 8*
FOR 21 Mev INCIDENT PROTON ENERGY.

A - Energy of deuterons from reaction (1)
B - Energy of deuterons from reaction (2)
C - Thickness of copper (in mg/cm^2) required to reduce deuterons from reaction (1) to 10 Mev.
D - Energy to which deuterons from reaction (2) are reduced by absorbers of Curve C.

The only other mechanism for production of Co 61 is by the reaction Co 59(α,2p)Co 61. However, the yield of this reaction must be considerably less than the yield of the (α,2n) reaction which produces the 3-hour activity of Cu 61. In the experiments on triton detection, the 3-hour activity in the copper fraction was somewhat less intense than the Co 61 activity, so that the (α,2p) reaction may be considered as a negligible contributor to the latter.

The methods described in connection with deuteron detectors for separating out long range groups and correcting for center-of-mass energy variation with absorbers are equally applicable in the case of tritons. The chief difficulty in triton detection experiments was found to be the low intensities. Only the most exhaustive counting techniques (each foil in a separate pig, tape recording, and extreme care in eliminating stray background) coupled with complete confidence that the chemical processing removes all short-lived activities except that due to Co 61 are sufficient for even rough measurements. Reliable measurements can only be obtained by several repetitions.

Elastic Proton Detection. The detection problem in experiments on angular distributions of elastically scattered protons is somewhat simpler than deuteron and triton detection because the particles being detected make up a large fraction of all particles present. The chief requirement is that the detectors be sensitive only to very high energy protons, so that inelastically scattered protons are not detected. Several reactions with high thresholds, such as (p,2n) and (p,pn), were tried but these were found to be far inferior to detection by (p,n) reactions with the detecting foils covered by a suitable absorber. Since the cross section is already known* and the half life is convenient, the reaction chosen was Cu 63(p,n) $\rightarrow$ Zn 63 $\rightarrow$ β^+ (38 minutes) + Cu 63.

* Blaser, J. P., Helv Phys Acta 24, 1 (1951).
Ghoshal, S. N., Phys Rev 80, 939 (1950).

Figure 2 shows the cross section for this reaction as a function of the proton energy incident on various thicknesses of covering aluminum absorber. The thickness is chosen so that the detection cross section for the elastically scattered protons is at the maximum; this gives high intensity and minimizes the effects of small uncertainties in the proton energy. For light elements, stepped absorbers are used to correct for the variation of energy with angle due to center-of-mass motion. The absorber completely eliminates activities from deuteron, alpha, and high threshold proton-induced reactions. Due to the relatively high purity of ordinary copper foil, impurities present no problem. The only background activities are the 5-minute and 12.8-hour activities from neutron capture in copper. The former is eliminated by delaying about 30 minutes before counting, and the latter is made negligible by counting under a 200 mg/cm^2 aluminum absorber. The absence of other activities and the convenient half life make the experiment sufficiently simple that one person can measure three complete angular distributions per day.

Target Cooling and Intensity Considerations

One disadvantage of activation detection is the need for high intensities. The counting rate obtained from a detector, after a saturation bombardment, is equal to the current incident on the target times the product of four efficiencies:

E_1, the probability for the reaction being investigated to take place in the target. For 25 mg/cm^2 target of atomic number 50, this is $3 \times 10^{-7} \sigma_1$, where σ_1 is the cross section for the reaction in millibarns.

E_2, the geometric efficiency, which is the area of the detecting foil divided by $4\pi r^2$, where r is the distance between target and detector. For 1/2" x 1/2" detecting foils and r = 3", this is about 1/400.

E_3, the probability for the detecting reaction to take place. Under the assumptions made for E_1, this is $3 \times 10^{-7} \sigma_2$, where σ_2 is the cross section for the detecting reaction in millibarns. For $\sigma_2 \approx 200$ mb, $E_3 = 6 \times 10^{-5}$.

E_4, the counting efficiency, which can be made as high as 1/2, but a more typical value is 1/4.

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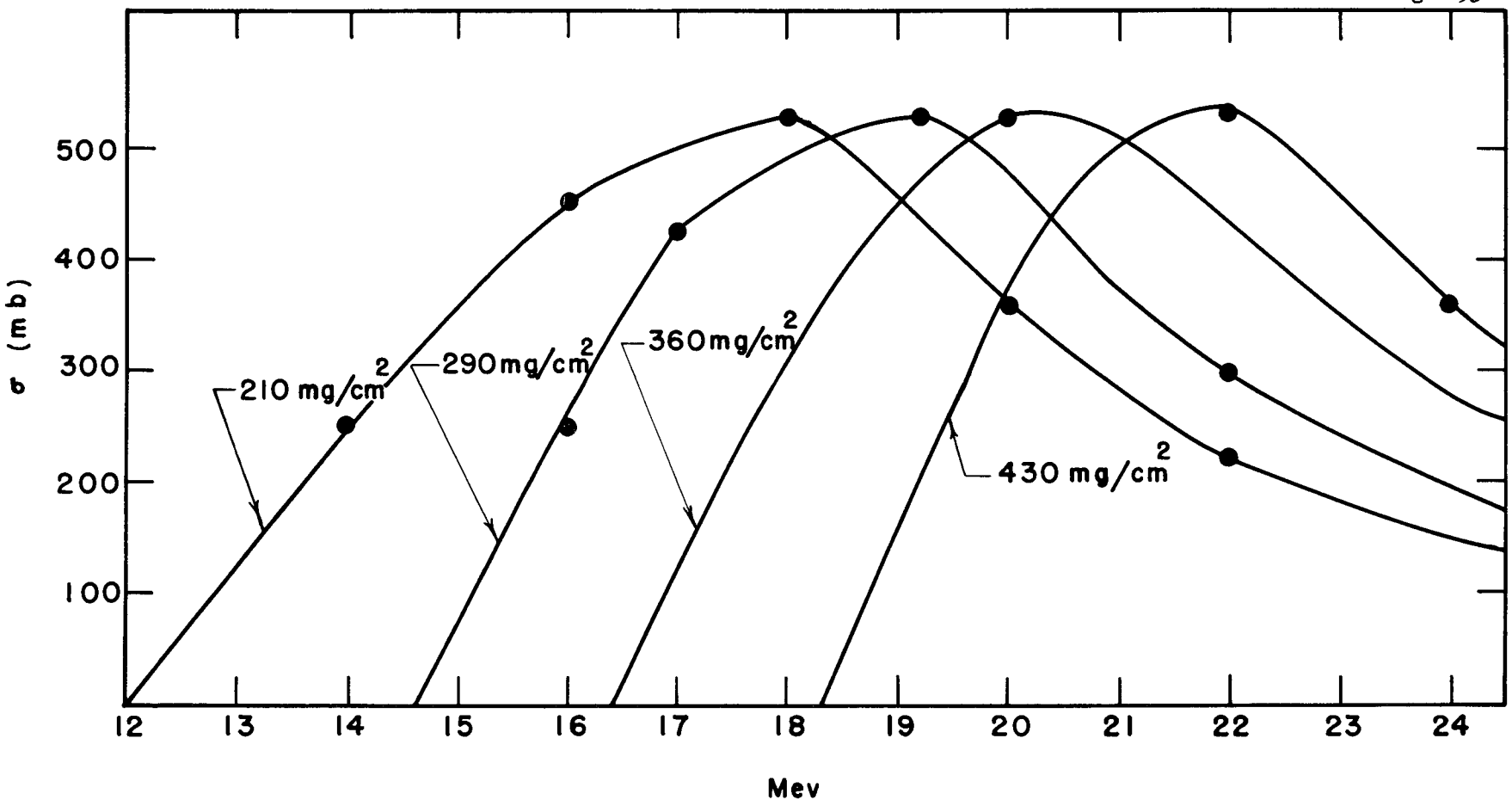

FIGURE 2. CROSS SECTION FOR THE Cu 63(p,n)Zn 63 REACTION as a function of proton energy incident on various covering absorbers.

For a 15 μa current on the target--this is about the highest possible, as will be pointed out presently--and assuming the typical values discussed above, the final counting rate is about σ_1 c/sec. Counting rates less than a tenth of a count per second become quite difficult to handle, so that the method is limited to primary reactions with cross sections at least as large as 1/10 mb. Of course, many of the factors in the above calculation vary. For example, a beryllium target increases E_1 by a factor of six; a non-isotropic angular distribution can increase E_2 at some angles by a factor of five or more; in some cases, E_3 can be increased by using thicker detectors. On the other hand, for particles such as tritons, the effective detector thickness and cross section are somewhat less than the typical values above; bombardment to more than half-saturation increases long lived background activities unduly; chemical processing requires time; and not many targets can withstand 15 μa currents. Taking everything into consideration, the original estimate of 1/10 mb minimum primary reaction cross section is probably a good all-round estimate. Convenient counting rates require cross sections at least 100 times greater.

From the above calculations, we see that the required currents are considerably higher than in counter experiments, and, in fact, the amount of current that a target can withstand is generally the severest limitation to the experiment. Table I shows the maximum current that can be dissipated by various targets assuming radiation cooling with the material at a temperature just below its melting point. When the magnetic field is tuned accurately, the width of the beam has been found to be about 1/8" with peak current densities about 2 or 3 times the average.* As an example, we should expect a 1 Mev thick beryllium target 1/2" wide to withstand currents as high as 10 μa.

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* Cohen, B. L., Spatial Distribution of Current on an Internal Cyclotron Target, ORNL-1348, July 1952.

TABLE I: MAXIMUM CURRENT THAT CAN BE DISSIPATED BY VARIOUS TARGETS*

Target Element	Thickness per Mev (mils)	Maximum Current μa-Mev per cm^2
Al	7.4	10
Be	10.8	80
Bi	4.5	1
Cd	4.2	1.5
C	10.0	2400
Co	3.2	120
Cu	3.2	38
Au	2.3	38
In	4.9	0.1
Fe	3.5	130
Pb	3.5	1.5
Mg	11.5	9
Mo	3.1	860
Ni	3.1	110
Pd	3.2	135
Pt	1.9	210
Ag	3.4	28
Ta	2.4	1350
Th	4.0	240
Sn	5.0	0.6
W	2.1	2000
U	2.3	50
Zn	3.9	3
Zr	5.0	260

* With temperature just below the melting point of the material and assuming radiation cooling of the target.

In practice, average currents about one-third those calculated in this way must be used, probably because of momentary surges in beam intensity.

By running the cyclotron with the magnetic field somewhat higher than resonance, the beam can be spread over the target more uniformly, allowing currents about twice as high as in the resonance case. This device reduces the angular resolution and increases background, so that it is used only where intensity problems are severe.

Current Monitoring and Measurement

Since the target is not water cooled, measurement of current by conventional methods is impossible. As a substitute, two methods are used, one for monitoring the current during the run as a guide to cyclotron operation, and the other for determining the absolute differential cross section. The first consists of a conventional paraffin-encased boron-trifluoride neutron counter placed a convenient distance from the cyclotron. The counting rate is roughly proportional to the current striking the target, so that, with a moderate amount of experience, the proper level of cyclotron operation can be determined in terms of this counting rate. In most cases, this is the maximum current that the target can withstand without melting away.

In order to determine the actual target current, the target is removed several hours after the end of bombardment and counted in a standard geometry under an end window Geiger counter with a convenient absorber interposed. The counting rate at a given time after the bombardment is proportional to the integrated current on the target. In order to convert this counting rate to microampere-seconds, a calibration run is necessary. A foil stack, consisting of a piece of the target foil put in front of several copper foils, is placed behind a "window frame" of thick (that is, full range for 22 Mev protons)

tantalum, and bombarded in the cyclotron. The purpose of the window frame is to make certain that all protons striking any foil in the stack strike all foils. To find the current, the copper foils are surveyed to determine the one with the most intense radioactivity. Since practically all the activity is the 38-minute decay of Zn 63 from Cu 63(p,n), the proton energy at this foil must be that at which the cross section of that reaction is a maximum. The maximum cross section (which occurs at about 13 Mev) is 530 mb.* The foil is dissolved and an aliquot is made and counted close to the window of an end window Geiger counter to determine the 38-minute activity. The current is then calculated, based on a cross section of 530 mb and a counting efficiency slightly less than 50%. By basing the calibration on the maximum of the cross section, the errors due to energy uncertainty and inhomogeneity are minimized. Any appreciable error in the counting efficiency seems unlikely; but even these cancel out in the calibration for elastic proton angular distributions (these require the most accurate calibration) since the detecting foils are copper, counted under the same geometry for the same activity.

The pieces of target material are counted in the same geometry and the same absorber conditions as those in which the targets are counted. Since the current on this run is determined by the copper, the desired calibration of these counting rates is obtained. It is not necessary to know the source of these activities--in most cases they are a combination of various activities and usually due to impurities. Since the target material is counted a long time after the end of bombardment, the activities are all long-lived so that errors due to decay during bombardment are negligible. Two targets are calibrated in a single calibration run since they are quite thin and very few reactions have cross sections which vary rapidly in the region of 22 Mev.

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* Ghoshal, S. N., Phys Rev 80, 939 (1950).

Determination of Angles and Angular Homogeneity

The angle between the incident and emerging particles may be determined by geometric measurements and a knowledge of their radius of curvature (i.e., the energy), if the location of the center of curvature of the incident proton beam is known. The energy determines its coordinate in the direction normal to the direction of the beam at the target (the x-coordinate). Actually, the determination of angles is quite insensitive to this coordinate. The other coordinate of the center of the curvature (y) is determined at regular intervals by one of two methods.* The first method employs a specially designed long target with a tantalum plate at one end. Several lead foils protruding above the tantalum are placed at regular intervals along the length of the target. The target is then bombarded, burning out the lead foils until the beam strikes the tantalum. The pattern formed by the tops of the lead foils shows the trajectory of the outermost ion orbit, thus giving the y-coordinate of the center of curvature. The trajectory, as determined by the tops of the lead foils, is circular with a radius approximately equal to the radius of curvature of the protons as determined from their energy. This indicates that the y-components of the centers of curvature of the protons in the beam are not widely distributed. A spread of no more than 1/2 inch seems to be indicated which is roughly the same as the spread of the x-components as determined by the energy distribution in the beam. It may be shown by a geometric argument that a 1/2-inch spread gives an angular inhomogeneity of a little less than one degree. This is about the same amount of inhomogeneity as is introduced by the finite radial width of the cyclotron beam on the target.

* These measurements were made by J. A. Martin, in connection with another project.

The second method consists of bombarding a flat plate and making a radioautograph. The cut-off of the activity determines the y-component of the center of curvature.

These two methods, combined with geometric measurements, determine the angles with an uncertainty of about a half degree. Two methods of checking the angles are available from experiments on angular distributions of elastically scattered protons. For heavy elements, the Rutherford cross section must be valid at small angles. This implies that the angular distributions must obey a $\csc^4 \theta/2$ law, and gives an absolute value for $\sigma \sin^4 \theta/2$. If an incorrect value of the angles is used, the angular distributions deviate monotonically from the $\csc^4 \theta/2$ dependence, and the absolute value of $\sigma \sin^4 \theta/2$ does not check the predicted value. Each of these methods gives a determination of the angle to within less than one degree.

Elimination of Background

While the solutions of the problems discussed in the previous sections were more or less straightforward, for some time there was considerable doubt about the feasibility of the entire program because of the difficulty in eliminating background. Background was measured by bombarding either with the target removed, or with a thick lead absorber between the target and detectors. It was eliminated only after a long series of experiments in which various types of shielding were tried. This was made especially difficult by the fact that the background was extremely variable from run to run, for reasons that seem completely inexplicable. In addition, it came from directions which defy the imagination for explanation, apparently following orbits several inches outside what is normally considered the outermost orbit, and orbits that can

be followed only by negatively charged ions. Some of the more important general methods that were used are the following (reference is made to Figures 3 to 7):

Use of Carbon for Shielding and Stopping Beam. Carbon has four very considerable advantages: it is easy to cut, file, drill, etc., which was quite important in the development period when changes were made frequently; it withstands high temperatures; its (p,n) threshold is so high ($\sim$19 Mev) that it produces very few neutrons as a result of proton bombardment, and especially few with sufficient energy to initiate (n,2n) and (n,p) reactions which were originally important contributors to the background; and it has no long-lived proton-induced radioactivities which would make target handling very difficult. For deuteron and triton angular distribution, carbon is especially valuable since production of those particles with sufficient energy to be detected is energetically impossible with 22 Mev protons incident on carbon.

The Large Beam Stopper. The greatest single step toward reducing background was achieved by replacing the original beam stopper, which was only about three times the width of what is normally considered the cyclotron beam, by one about ten times wider. The reason for this is obscure, but it was this step that changed the project from a faint and despairing hope to a promising program.

Box Shielding . Backgrounds of charged particles can always be eliminated by placing the detectors in a thick closed box, but this is impossible, of course, because the particles to be detected would also be removed. The next step might be to remove the side of the box from which these come, in our case, the top. However, this exposes edges, so that it introduces the problem of scattering from edges into the detectors. Fortunately, this problem was found to be far less serious than originally feared.

By beveling the edges and keeping them well below the intense part of the incident beam so that a particle scattered from the top cannot reach the detectors without additional scatterings, all edge scattering was made negligible except for small angle scattering of particles coming from the direction of the incident beam. This is not serious since it gives background in the direction in which the protons scattered from the target are most numerous.

At this point the only important remaining problem was a background on the detectors at angles larger than about 80°. This was found to be coming from the general direction of the beam stopper, although particles coming from the beam stopper itself would require several scatterings before they could reach these detectors. There is some possibility that they may be negative ions in off-center orbits; they pass through absorbers that would stop 18 Mev protons, and produce the activities of (p,n) reactions. It was thought that these might be eliminated by proper placement of the beam stopper but an extension of the "box shielding" method was found necessary, as will be described in Section II.

Wrapping Detectors. In the early experiments unexplainable activities were observed which were always eliminated when the detectors were covered by absorbers. It was found that wrapping the detectors with very thin (1.3 mg/cm^2) aluminum foil served equally well, and this is now done routinely. Evidently the activities are from radioactive atoms evaporated from the target and the other places exposed to the beam.

Miscellaneous Problems

Radiation Hazard. The activity on the target assembly after a typical run ranges from about 1 to 10 curies, so that radiation of personnel while removing the detectors is a serious problem. This is alleviated somewhat by the use of lead face mask, apron, and gloves, but the most important measure is to reduce the time spent near the target. At present, one detector insert can be removed and another inserted with long tweezers in approximately 15 seconds. This gives a body exposure of about 10 mr and a hand exposure of about 75 mr.

Heat Dissipation. While a very considerable amount of heat is generated in both the carbon beam stopper and the target, the assembly base must be kept relatively cool, especially when lead detectors are used. The beam stopper is suspended on thin (1/32") tantalum strips which provide a poor path for heat conduction. In addition, a mica sheet is placed on the end of the detector holder to shield it from thermal radiation from the beam stopper. Both of these steps were found to be very necessary. A difficult conduction path from the target to the assembly base is also provided. In addition, a small amount of cooling water is run through the assembly base.

RF Sparking. At various times considerable difficulty was experienced with rf sparking from the dees to various parts of the target assembly. This is minimized by rounding all edges and corners as much as possible, as may be noted in the pictures. In addition, the target is run at the largest possible radius to maximize its distance from the dees. Even with these precautions satisfactory runs are possible only when the cyclotron vacuum is below about 0.1 micron.

Alignment. To insure duplication of alignment from run to run, an alignment jig was built. This jig is essentially a pendulum with the center of curvature of the beam simulated by the point of suspension of the pendulum

and the beam path indicated by the tip of the bob. A rigid platform holds the assembled target in the same position with respect to the pendulum that it occupies in the cyclotron with respect to the beam. Each time the apparatus is assembled for a series of three runs, the beam stopper is jig aligned. The target is also aligned with the jig and its position checked with respect to the assembly base.

Duplication in the location of the detector foil from run to run is insured by a scribed line on the insert which is in turn pinned to the assembly base. The relative angles of the scattered protons received by each segment of the detector foil can be measured to 1/2 degree.

II: DESCRIPTION OF TARGET AND PROCEDURE

Figure 3 shows a disassembled view of the apparatus for detecting the angular distribution of elastically scattered protons. Figures 4, 5, and 6 show succeeding stages of assembly and Figure 7 shows the assembled apparatus ready to be installed in the cyclotron. The parts are named and numbered as follows:

1. Assembly base (aluminum)
2. Cooling water header (brass)
3. Side shield (carbon)
4. Assembly base shield (carbon)
5. Beam stopper (carbon)
6. Bracket (tantalum)
7. Heat shield (mica)
8. Insert (aluminum)
9. Absorber (aluminum)
10. Detector foil (copper shown)
11. Wrapper (aluminum)
12. 45° shield (aluminum
13. Pin
14. Target (tantalum shown)
15. Clamp strip (tantalum)
16. Target holder (aluminum)
17. Target shield (carbon

The assembly base (1) locates and holds in position the insert with its proton detecting foil (8) and (10) and the target holder with its target (16) and (14). A water passage next to the water header (2) permits cooling water to flow along the length of the base. Side shields (3) were found to reduce the background, especially in the 80 to 110° region. The edges are so shaped that scattering in the direction of the detector foil is minimized. The beam stopper (5) made of carbon, stops all of the beam that is not scattered by the target. Tantalum brackets (6) and tantalum screws and nuts which hold the beam stopper in place are necessary to prevent melting at the high temperature to which it is subjected. A mica heat shield (7) partially shields the

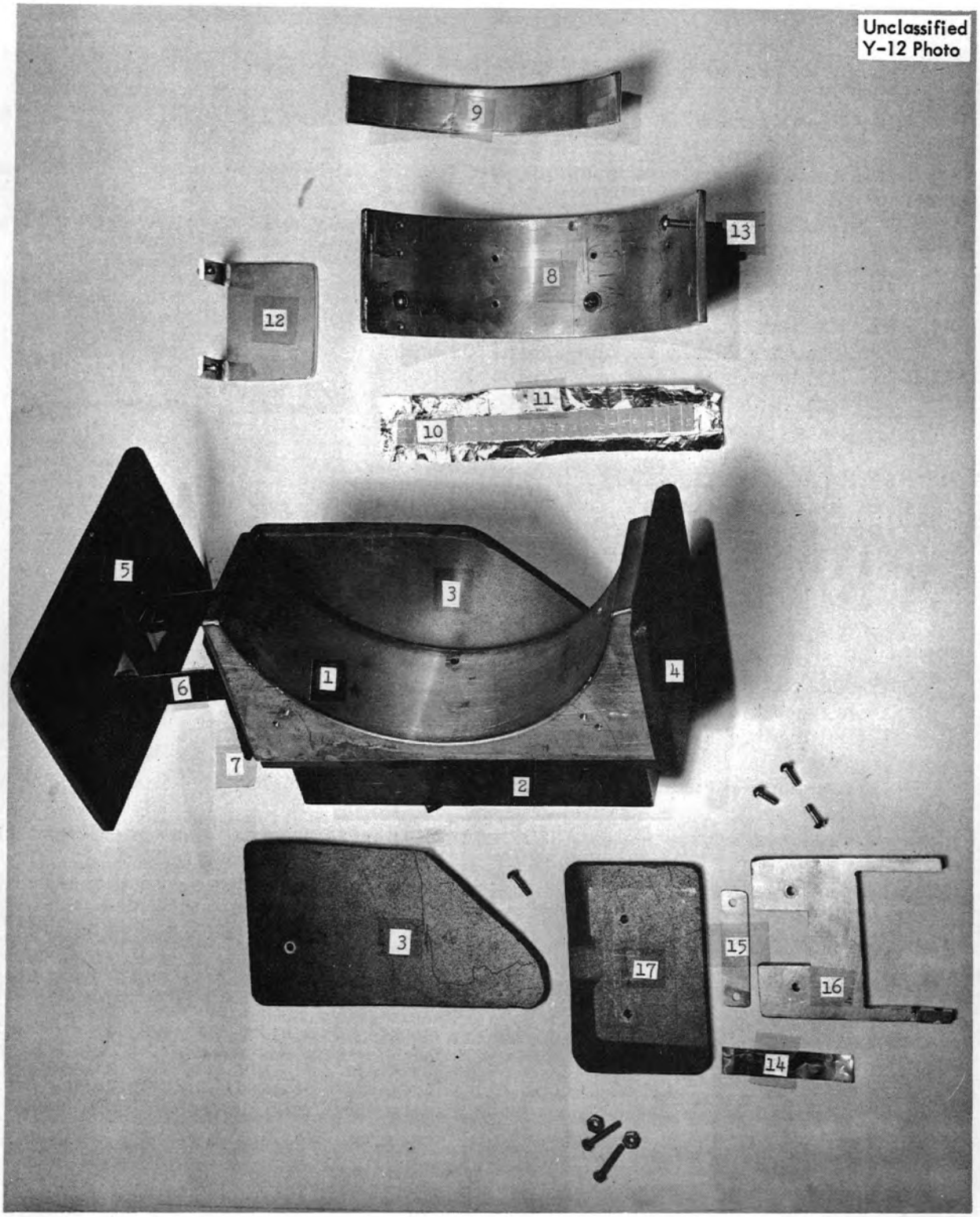

FIGURE 3

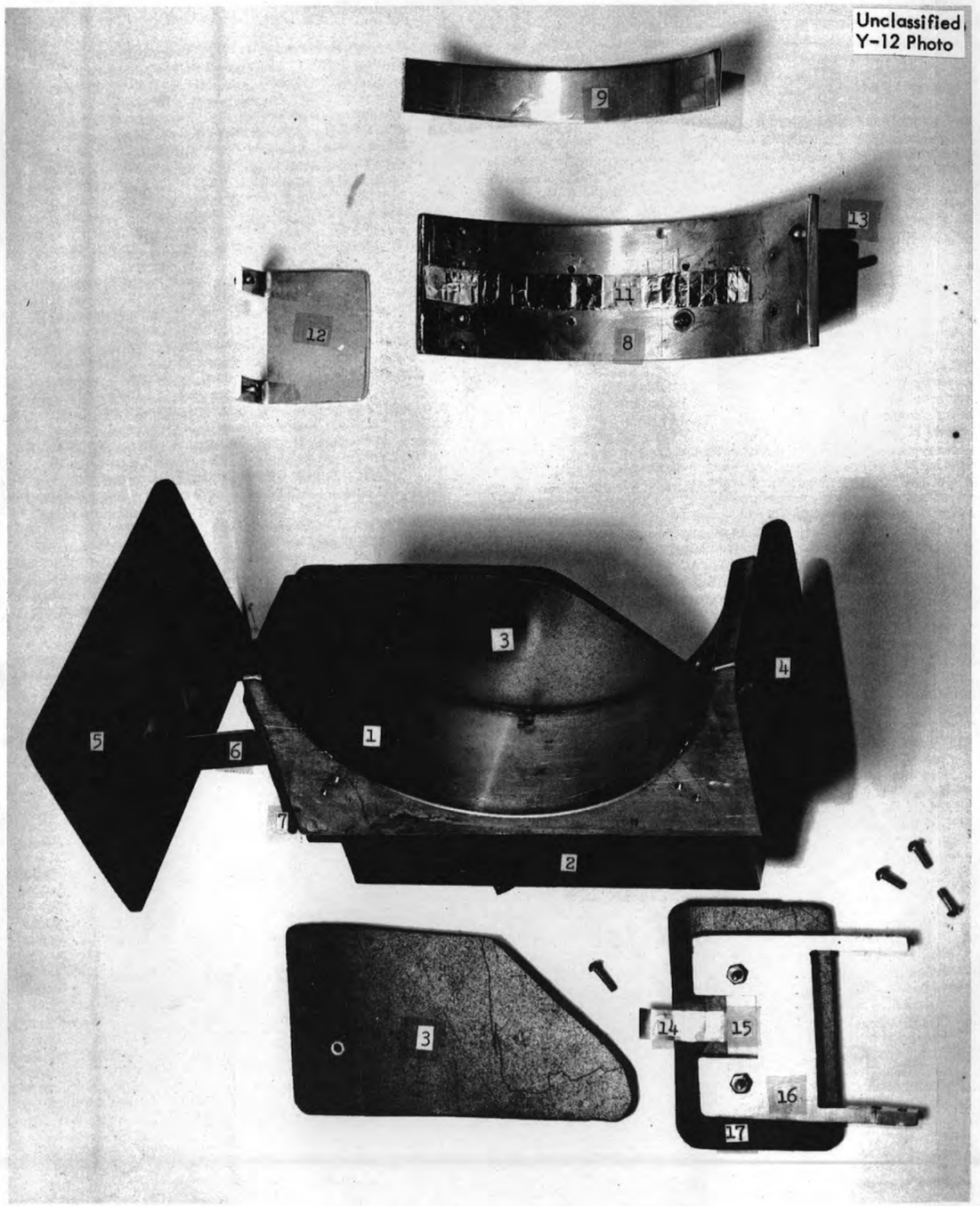

FIGURE 4

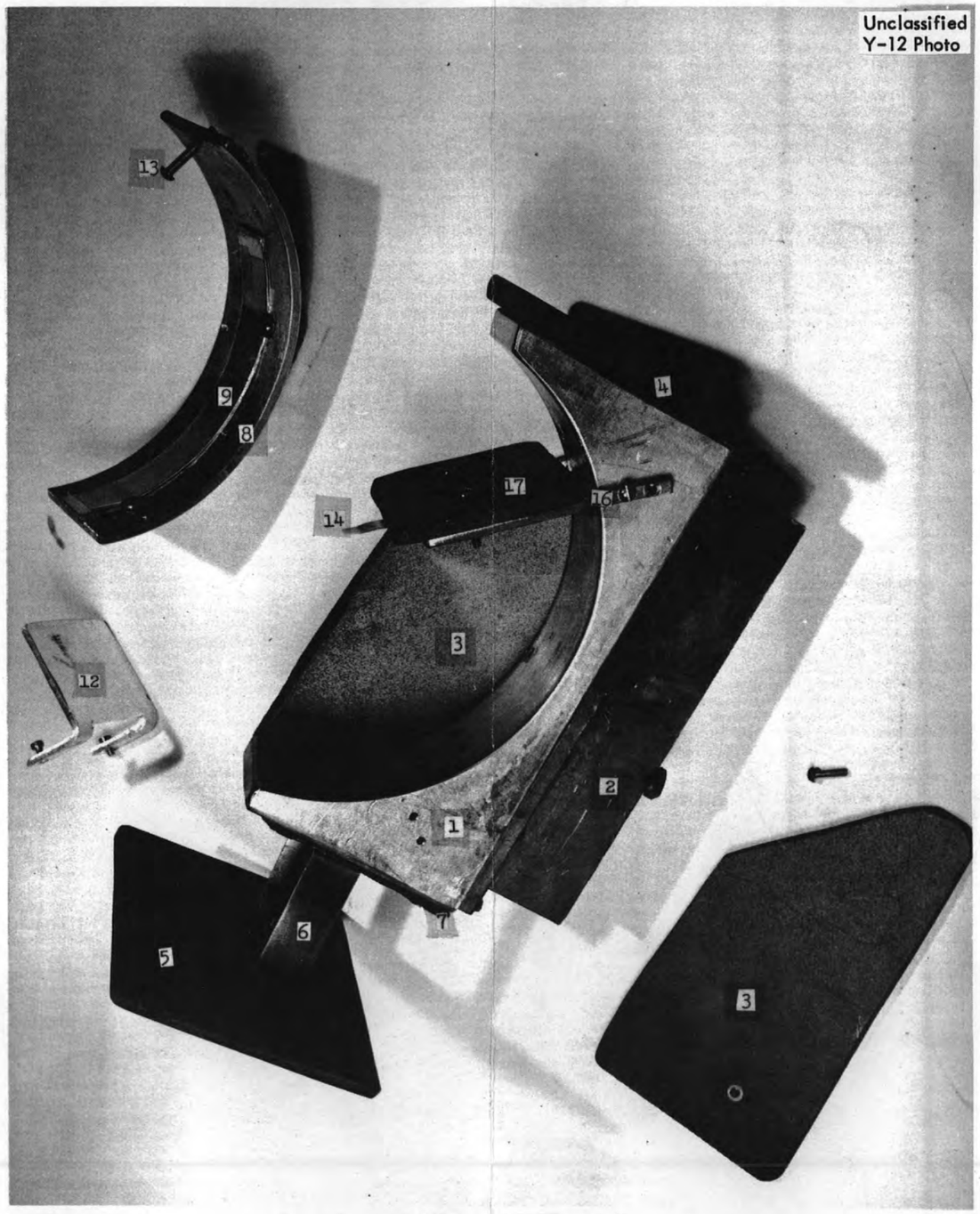

FIGURE 5

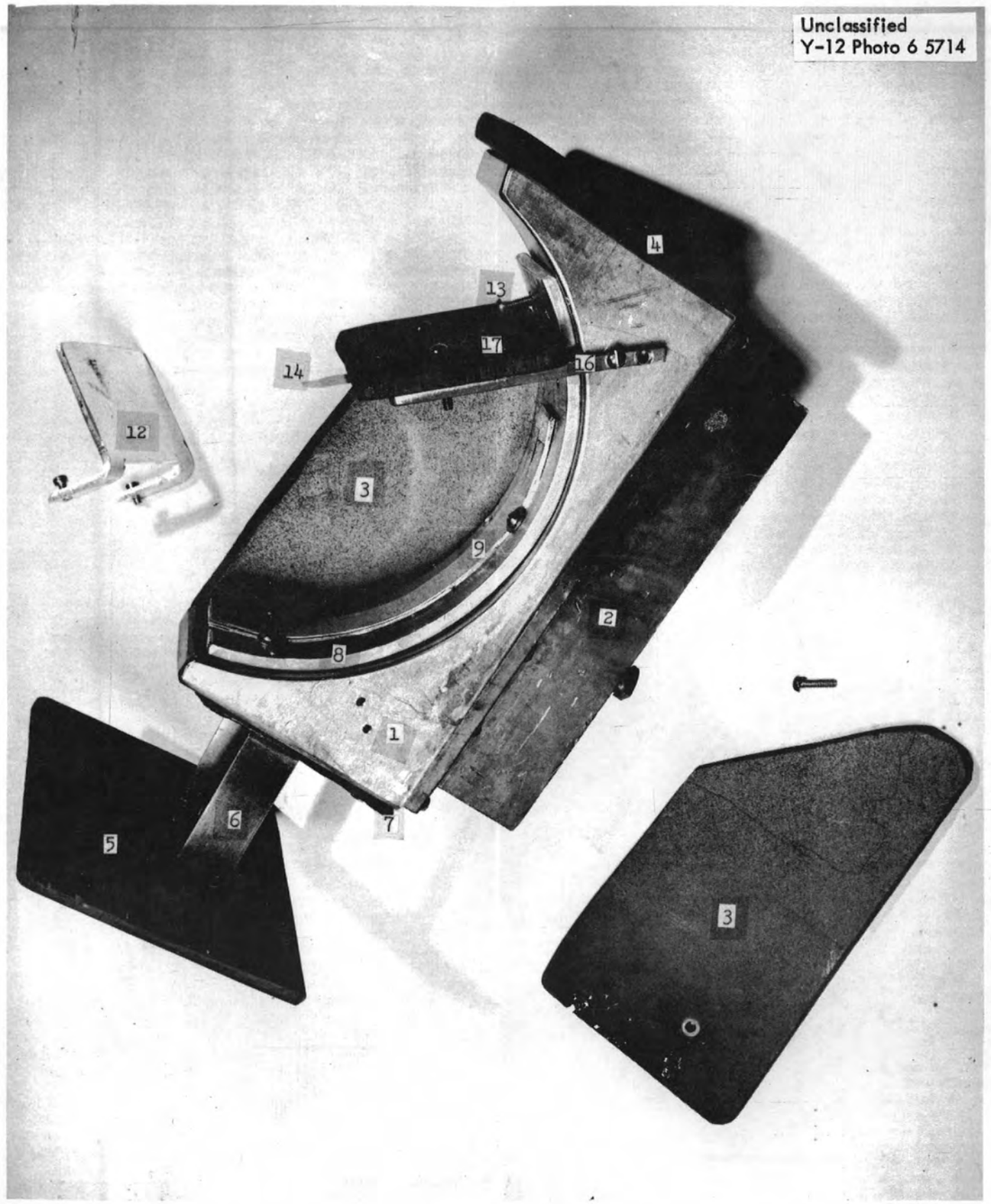

FIGURE 6

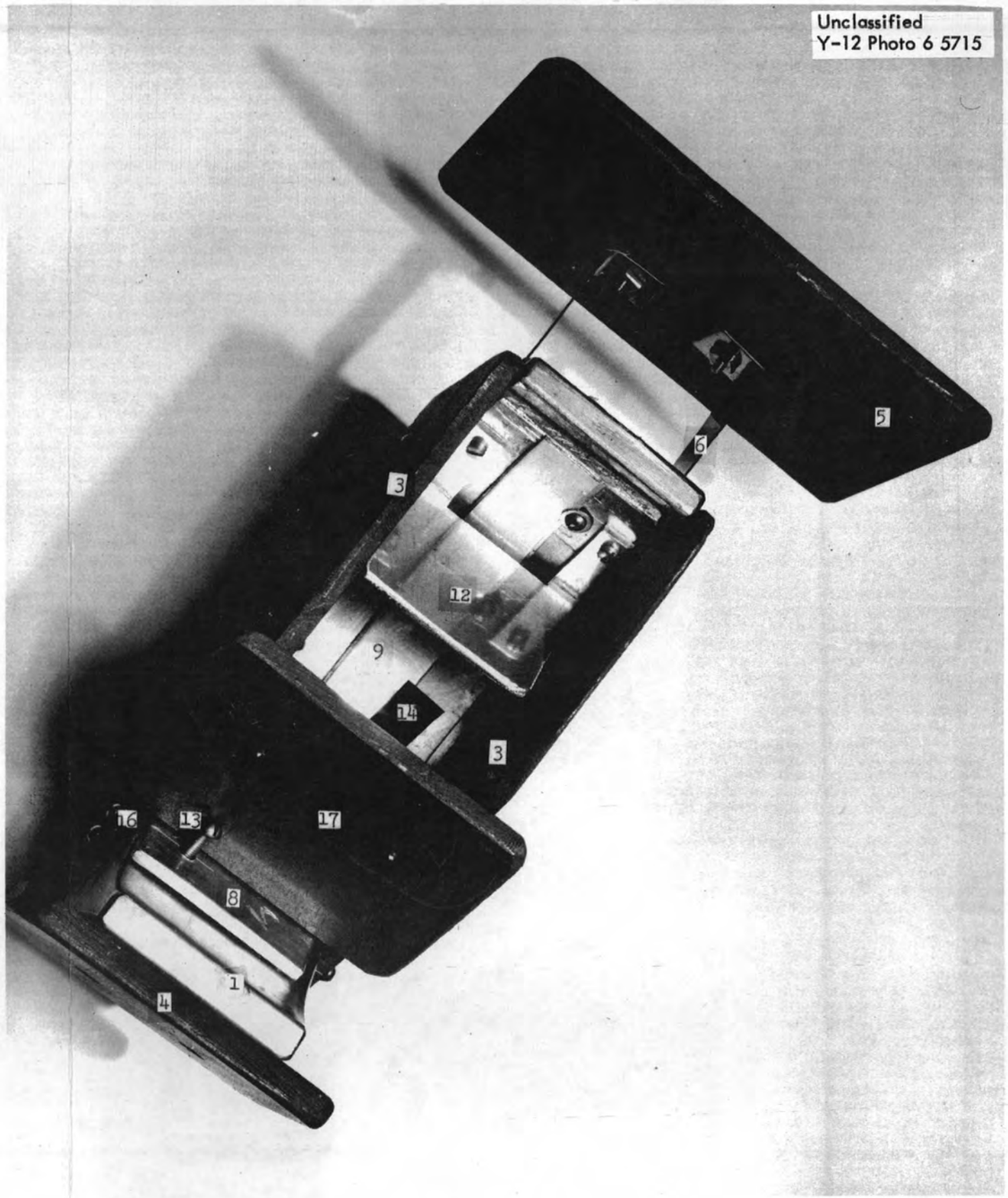

FIGURE 7

assembly base from the beam stopper. The assembly base shield (4) collimates the target edge of the beam and is shaped so that scattering in the direction of the detector foil is minimized.

The aluminum insert (8) is essentially a quick-change holder for the detector foil (10). It is located and held in place by one easily-removed pin (13). Several runs with the same target can be made by changing only the assembled insert. A copper detector foil (10) ruled and numbered with its aluminum wrapper (11) is held in place on the insert with two screws and washers. The numbers on the foil indicate the position of each piece. After the run, the foil is cut along the ruled lines and the pieces counted separately. The 45° shield (12) is aluminum approximately 2" by 2" by 1/8". Its purpose is to remove the background at angles greater than 80°.

The tantalum target shown (14) is clamped to the carbon target shield (17) with a tantalum clamp strip (15). The target shield which shields the small angles of the detector foil is in turn located and held in position on the assembly base by the aluminum target holder (16). The target loses heat principally by radiation, since the conduction path is through the clamp strip and carbon shield to the target holder.

One set of data which indicates the scattered proton distribution from 10° to 110° is obtained by three successive runs. The first run is made with the assembly as shown in Figure 7. The 45° shield (12) is used in this run to eliminate the background in the large angle region. If an energy measurement is desired, the copper foil stack is placed on the insert at about the 25° position. The second run is like the first except that the 45° shield is removed as shown in Figure 6. This permits examination of the region near the 45° point and gives a double check on the small angles. The third run is a

background run and is like the first (45° shield in place) except the target is removed. The background induced activity of the third run is subtracted from runs one and two in the preparation of the data.

Several inserts are available so that a quick change is possible and the next run can proceed while the previous foil is removed and counted. The foil used in this experiment was 20 mg/cm^2 copper. A 1/2" by 6" strip was ruled so that it could be cut into 1/8" (2 1/8°) segments for the small angles (10° to 30°) and into 1/4" (4 1/4°) segments for the remaining length of the foil (30° to 110°). In some experiments a further reduction in size of the foils in the forward direction is made. Counting is not begun until at least one-half hour after termination of the run to reduce the effect of the neutron-induced 5-minute activity of Cu 66. The neutron-induced 12.8-hour activity of Cu 64 is minimized by counting through a 200 mg/cm^2 aluminum absorber. Each foil is counted three times in the next 1 1/2 hours and the 38-minute activity is plotted on semi-log paper. From this plot, the activity at the same time after bombardment is determined for each foil segment. Each foil is then weighed to correct for variation in the sizes of the segments. After several hundred decay curves were obtained and found to contain no activity other than the 38-minute, it was decided to count each foil only once and correct for the time of the count by calculation rather than by plotting.

In measurements of angular distributions of deuterons and tritons, proton background is not so important since it is removed chemically. Thus the side shields and 45° shield are omitted, and no background run is necessary. (A single background run was made and showed zero intensity at all angles.) In the deuteron case, neutron background is determined from lead foils attached to the back of the insert. After bombardment, the foils are cut into segments

and then counted for about 24 hours either under ordinary end-window Geiger counters with tape recording, or in a Tracerlab sample changer. The decay curves are plotted and the activity of the proper half life at a given time is determined for each foil. These are divided by the weight of the sample to determine the angular distribution.

III: SAMPLE RESULTS AND SUGGESTED APPLICATIONS

Up to the time of this writing, elastic proton angular distributions have been measured for nine elements with at least three runs on each, and in every case, each maximum and minimum has been reproduced on every run with the same target. Shift in their positions by as much as 4° has been observed from day to day (although not from run to run on the same day), probably due to changes in the energy distribution of the incident beam. The background is most serious at the largest angles, in a few cases becoming as large as 50%, although more than about 20% is unusual. At smaller angles (up to 75°) backgrounds larger than 1% are unusual.

The angular distribution of 22 Mev protons elastically scattered by aluminum is shown in Figure 8. The target thickness was 7 mg/cm^2 and the current was about 1/2 μa for 30 minutes. The data from a single run follows a smooth curve to within about 5%, but the variation from run to run is about twice that large, probably due to shifting of the cyclotron beam.

Figure 9 shows the angular distribution of the long-range deuteron group from the reaction Be 9(p,d)Be 8. Up to about 60°, the relative intensities can be determined with an accuracy of about 15%; at large angles, the neutron backgrounds are often two or three times larger than the deuteron-induced activity so that percentage uncertainties become very large. The absolute cross sections are difficult to estimate because they are very sensitive to the energy of the incident beam when absorbers are used over the detecting foils. The targets are 20 mg/cm^2 and are bombarded with about 5 μa for 1 1/2 to 3 hours. The chemical processing usually requires about six hours.

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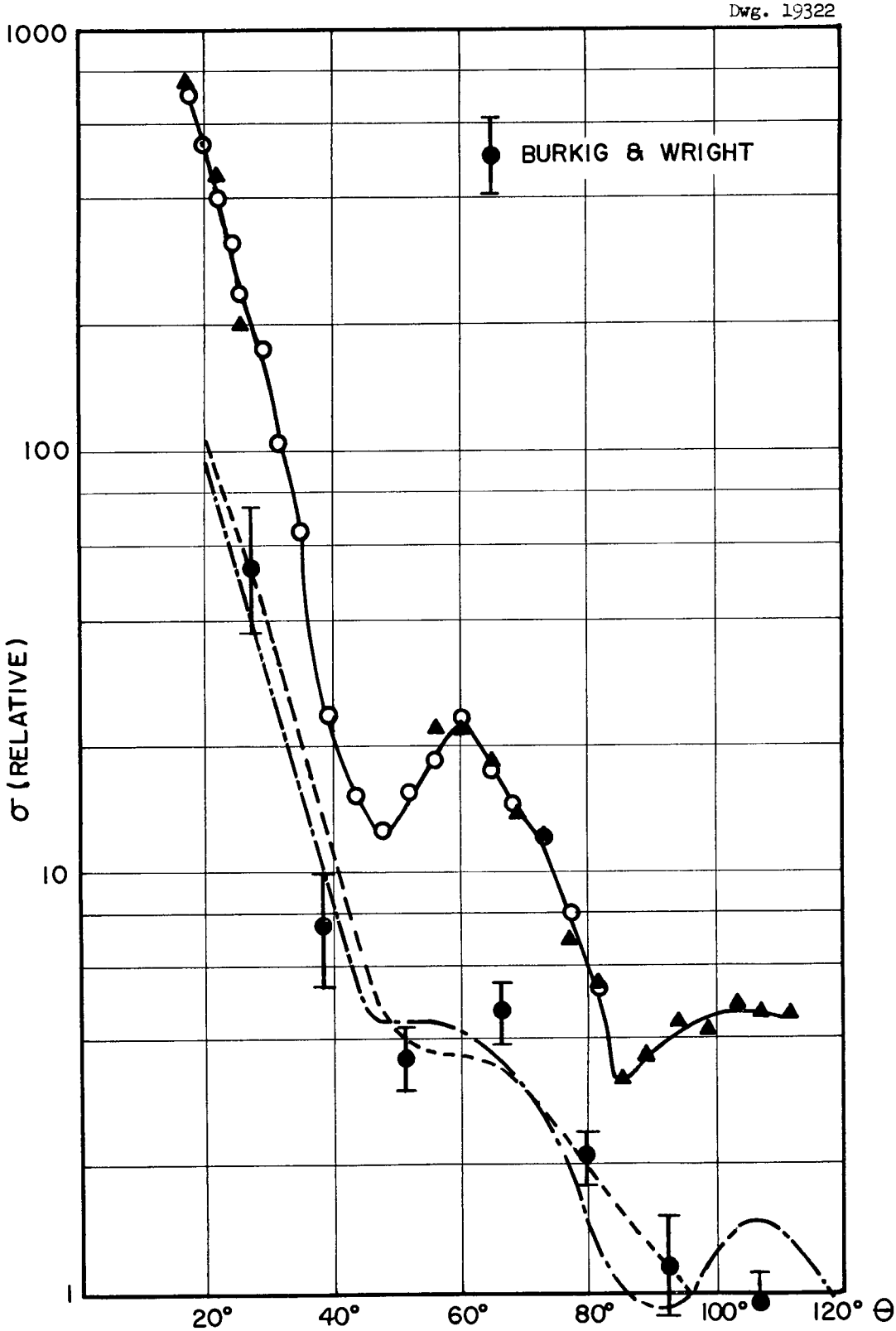

FIGURE 8 ANGULAR DISTRIBUTION OF 22 Mev PROTONS ELASTICALLY SCATTERED BY ALUMINUM

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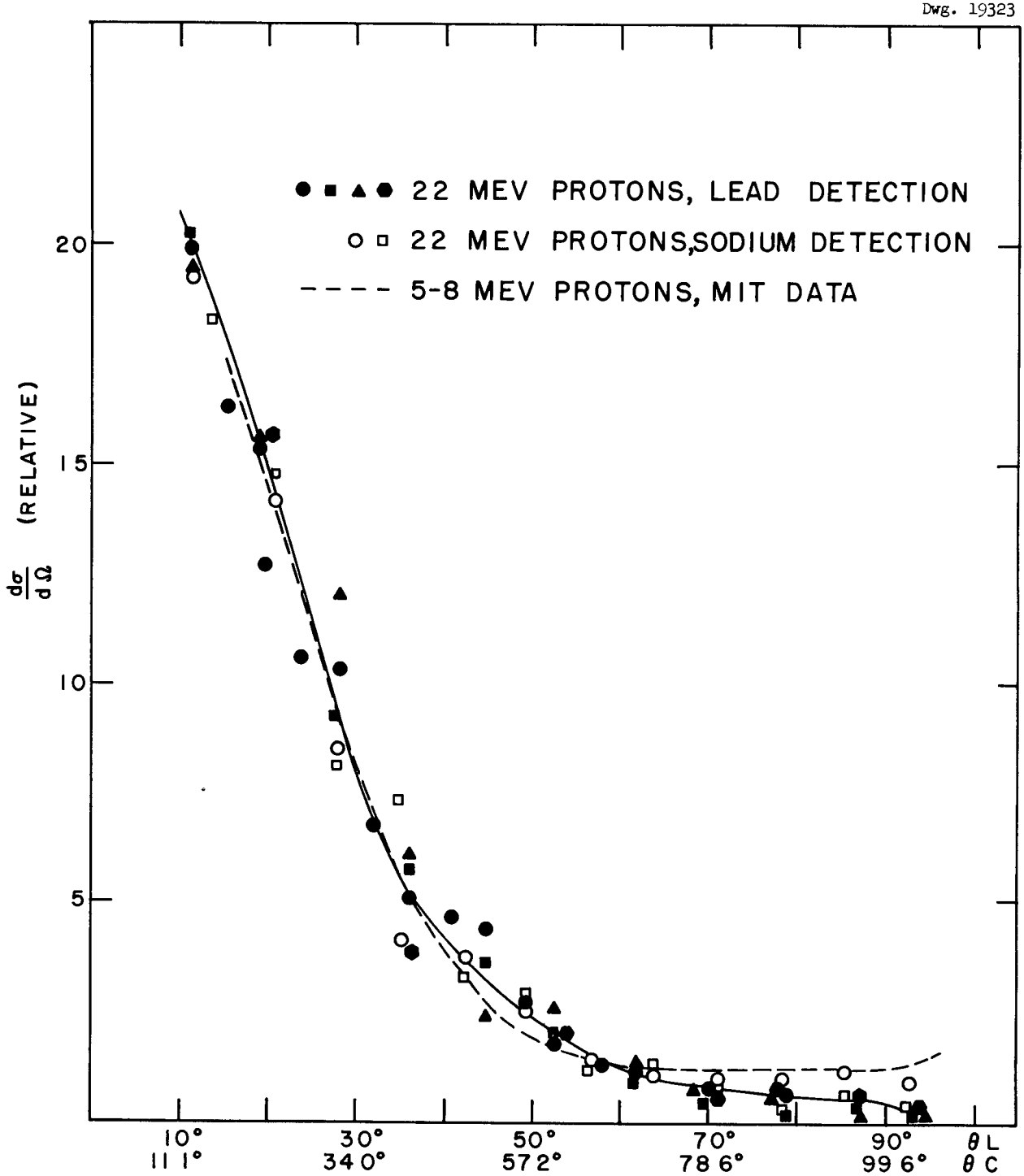

FIGURE 9 ANGULAR DISTRIBUTION OF DEUTERONS FROM
Be 9(p,d)Be 8 (Ground State)

Figure 10 shows the angular distribution of tritons from the reaction Be 9(p,t)Be 7 with the final nucleus either in its ground state or first excited state (440 kv). The absorbers reduce the triton energy at each angle to about 6 Mev. The targets were 20 mg/cm^2 and were bombarded with about 15 μa for 1 1/2 hours with the cyclotron detuned to spread the beam more uniformly over the target. The chemical processing required about two hours. Initial counting rates were seldom over $\sim$10 counts per minute so that uncertainties are about 25%.

Experiments currently underway include a survey of elastic proton angular distributions for about fifteen target elements, and a survey of angular distributions of deuterons from (p,d) reactions on various heavy elements. In the near future, it is planned to study the feasibility of measuring proton-deuteron elementary particle scattering with a LiH target fused onto nickel, and detecting the deuterons. The feasibility of measuring proton-triton elementary particles scattering will also be studied using a zirconium-tritium target and detecting the tritons. It is planned to cool the target by running water through a tube to which it is soldered.

Some preliminary work has been done on alpha particle detection. The reactions tried were P 31(α,n)Cl 34 β^+(33-min) + S 34, and Cu 65(α,n)Ga 68 β^+(68-min) + Zn 68. The phosphorous detection was performed by pressing pills of $AlPO_4$ and fitting them into a special insert with provision for holding them. After bombardments, the pills were counted under a thick absorber to eliminate the 170-minute activity of Si 31 from P 31(n,p). The copper detection requires chemical processing to remove the various zinc and copper activities that are present in great abundance. The final counting rates are quite low.

Unclassified
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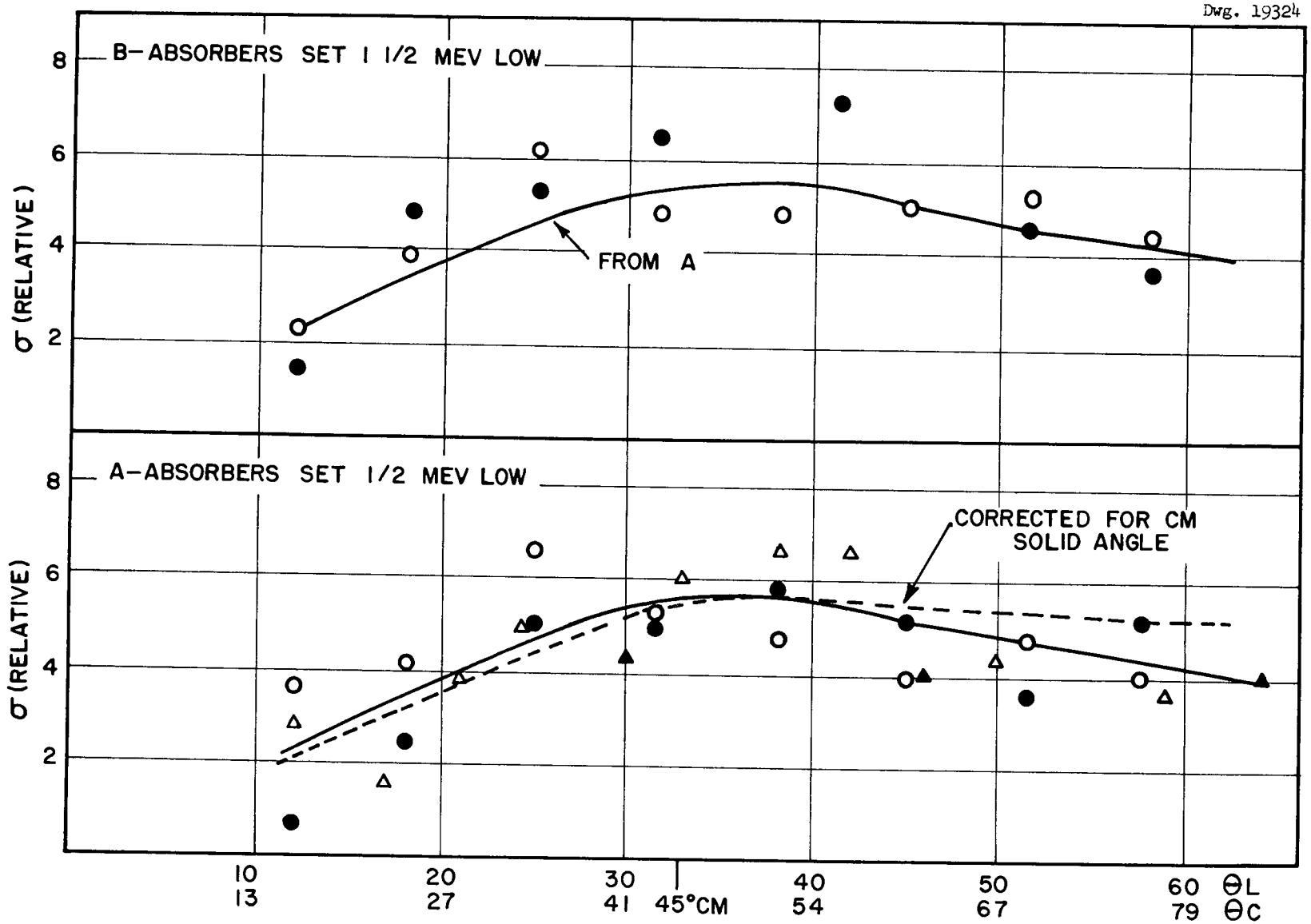

FIGURE 10 ANGULAR DISTRIBUTION OF TRITONS FROM $Be^9(p,t)Be^7$ (ground state)

A small amount of work was done on the angular distributions of the highest energy gamma rays from (p,γ) reactions. The detecting reaction tried was C 12(γ,n)C 11 β^+(20-min) + B 11 which has a threshold of about 19 Mev. The incident proton energy was reduced to 18 Mev (by running at a lower magnetic field) to eliminate the possibility of the (n,2n) reaction which produces the same end product. (The gamma rays would then have an energy of about 26 Mev.) If the cross section for the primary reaction were as much as one millibarn the experiment would have been successful, but no activity was detected. In the future, further work may be done with greater sensitivity.

Work on neutron angular distributions with activation detection has been carried out by Allen and others using thick targets.* It is planned to test the feasibility of performing this type of measurement with relatively thin targets.

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* Allen, A. J., Nechaj, J., Sun, K. H., and Jennings, B., Phys Rev 81, 536 (1951).