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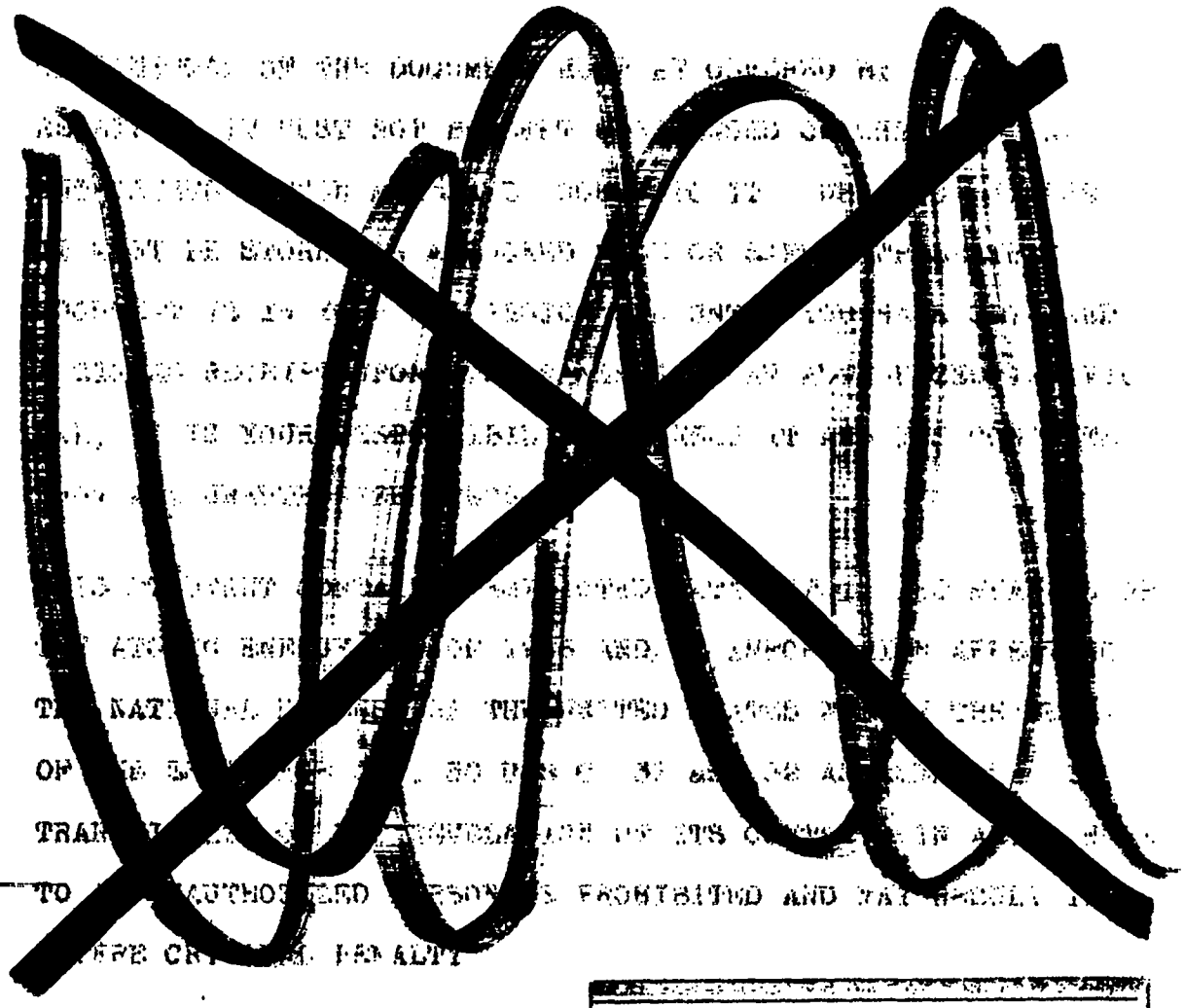

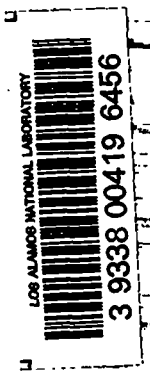

Physics - Cross Sections

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THE CROSS SECTION FOR REACTION 20(30,240)n

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THE CROSS SECTION FOR THE REACTION

20(30,240)n

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September 17, 1943

ABSTRACT

Measurements of the cross section for the reaction 20(30,240)n have been made, using a target about 0.2 Mev thick. The measurements made in a cone of approximately 30° about the direction of the beam give a thick target cross section which increases with increasing energy to a maximum value of 2.1 barns at 0.32 Mev and decreases to a value of 0.6 barns at 0.9 Mev. Measurements made in a zone at right angles to the direction of the beam indicate a peak value of 2.8 barns also at 0.32 Mev and a value of 0.7 barns at 0.9 Mev. These values are subject to final calculations of the solid angles.

TABLE OF CONTENTS

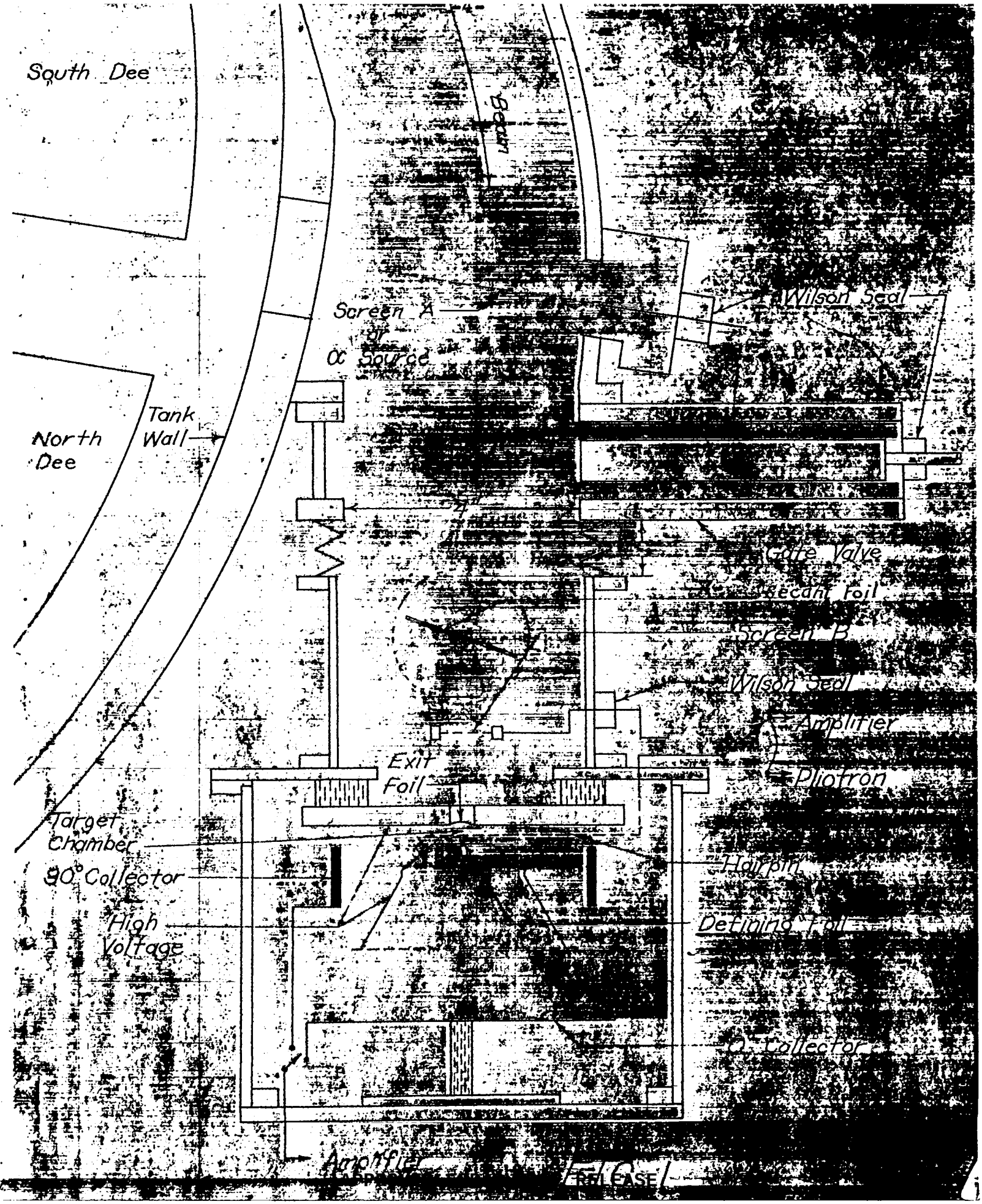
I-A. Statement of Problem and General Considerations.

This is a final report on the measurements made of the cross section for the reaction 20(30,240)n for incident energies of the 30's between 0.3 and 1.0 Mev. The experimental setup and procedure are essentially the same as those used in the 230 experiment. It is assumed that those concerned with this LAMS-2 report are familiar with the 230 report so that a detailed discussion is given only where the present work has differed from that in the 230 case.

The experimental arrangement is shown in Fig. 1 which is similar to Fig. 1 of the 230 report. A mica foil (known hereafter as the "secant foil") was mounted on a vertical axis in the region between the gate valve and screen B. The shaft supporting the foil projected through a Wilson seal and was equipped with a protractor disk and an index so that it could be set at any desired angle to the direction of the beam. This foil served the dual purpose of stopping the 10's and 20's accelerated in singly charged 10-20 molecules and of varying the energy of the 30's reaching the target chamber. The latter was particularly useful in that it was not necessary to change the inductance in the dee circuit in order to change the energy of the accelerated beam.

The 230 disintegration chamber, modified for the 30 experiment, is shown in Fig. 2.

I-B. Production of Beam. The source of the 30's used for bombarding was 60 cm^3 (at NTP) of gas containing 0.025% 30's. This sample of gas was supplied to us through the kindness of



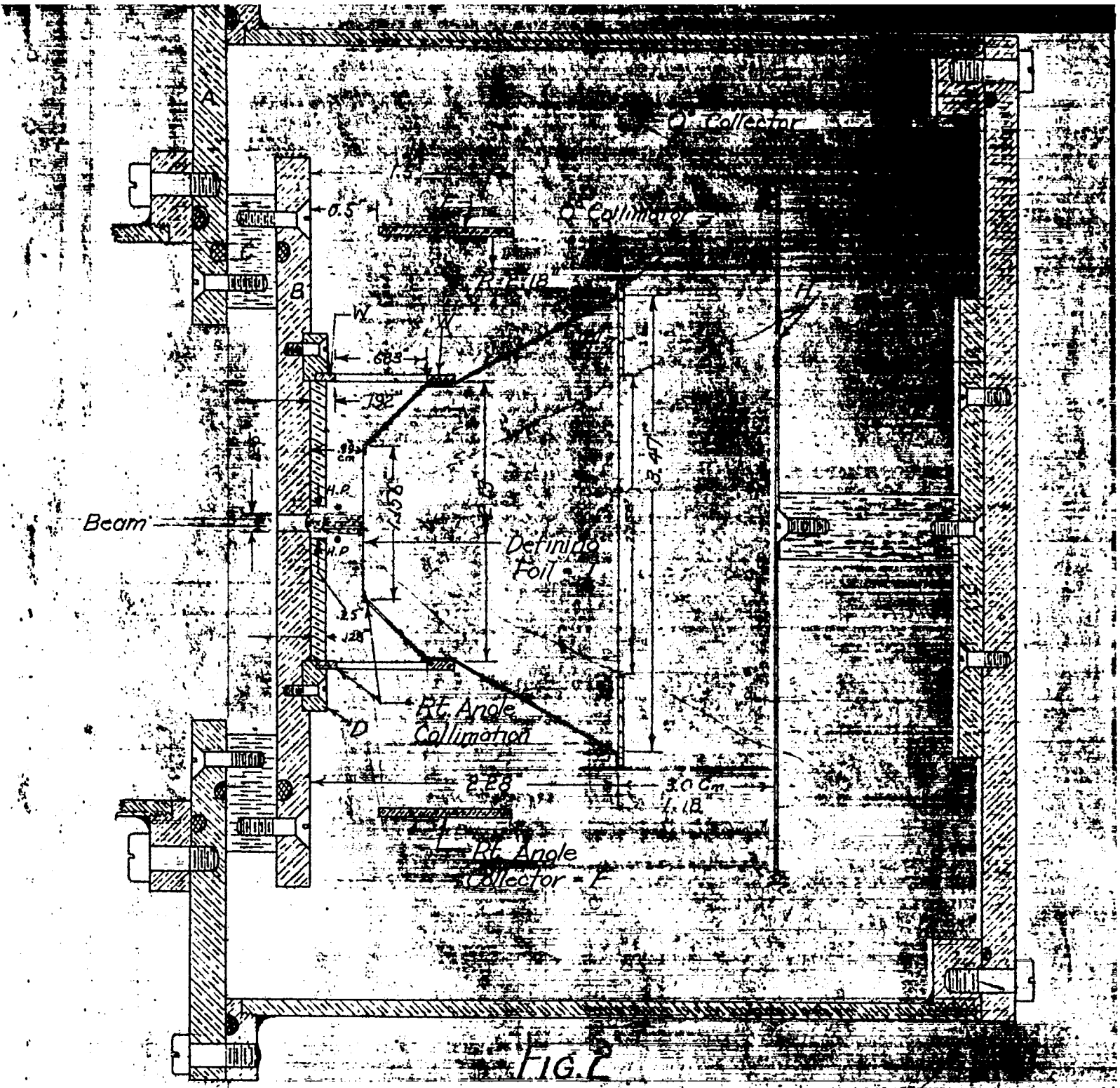


FIG. 2

DISINTEGRATION CHAMBER

Section Viewed From Side. Actual Size. E = Exit Foil. H.P. = .01 Wire. = Lucite = Round Rubber Gasket = Soft Solder. W-W .005" Ni Wires Spot-welded On Cylinder With ¼ Spacing. 0° Collimating Cone And Collector Are Cu. Other Parts Brass. Entrance Slit = .125" x .50". Foil Pulled In Av. .01 Cm By V... With...

Drs. Emilio Segrè and Milton Kahn. Rough calculations showed that a beam of suitable magnitude (2×10^5 particles/sec) should be obtained with a dilution of this gas of 1:1000 in ordinary tank 10 gas. This concentration was used during the period of cyclotron adjustment and in the initial disintegration experiments. A somewhat stronger concentration was used later to decrease the time required for each disintegration run. This gas was supplied to the same type of arc as used in the 230 experiment and, after the necessary shimming changes were made, a beam of about 5×10^5 30's per second was obtained.

The number and energy of the particles were found to be very sensitive to the cyclotron adjustments. A combination of electronic and manual controls was used to hold the field to within a few gauss and at times an adjustable capacity was used to maintain the desired frequency.

I-C. Target. The 20 gas used in the ionization chamber was purified by passing it through palladium. The gas was palladinized in advance and kept in a storage flask in contact with distilled water which had been previously boiled and subjected to a vacuum to remove dissolved gases. The gas was dried before entering the ionization chamber by passing through a trap cooled either with liquid air or a dry ice slush. Chemical analyses of samples from most of the runs have been made, and mass-spectroscopic analysis of the gas is being made by Dr. R.H. Urist of Columbia University.

I-D. Ionization Chamber. It was thought at first that the ionization chamber used in the 230 problem could be used for the 30 problem without any changes. This did not turn out to be the case and a great deal of time was consumed in locating and remedying the troubles which appeared. The difficulties finally were resolved to the following: 1) In the energy interval being used, the relative stopping power of mica and aluminum is much smaller than the values usually assumed; 2) through an error in preliminary calculations, the magnitude of the variation of the energy of the disintegration 240's with the 30 bombarding energy was underestimated, and 3) 30's are strongly scattered by aluminum. These difficulties led for a time to erroneous results and are of sufficient interest to warrent discussing each of them in some detail.

1) The fact that the stopping power of aluminum and mica was low was first suspected in connection with the behavior of the secant foil. What was believed to be a sufficient thickness of aluminum was first used and it was found at once that 20's were able to reach the target chamber in appreciable numbers. Non-uniformity of the foil was suspected and a mica foil of 7.1 mg/cm^2 ($R = 5$ cm) was substituted. This mica foil still allowed 20's to enter the target chamber in a less degree. It also possessed an apparent flaw which did not show up under polarized light but made the foil thin at a certain angle to the direction of the beam.

The air equivalent of the mica foil was measured by observing the variation of the energy of the 30's in the target

chamber as a function of the angle of the foil to the direction of the beam(and hence as the foil's effective thickness was changed). The value found in several such measurements was consistently less than half of what was expected from the thickness in mg/cm^2 of the foil.

The first mica foil was therefore replaced by a thicker foil of 8.5 mg/cm^2 which was used throughout the rest of the work. Tests of its stopping power have also given values about half of that normally to be expected. The rate of energy loss for 30's is expected to be the same as that of 10's of the same velocity or of 1/3 the energy so that the value of the relevant stopping power for 1.0 Mev 30's must be obtained from the stopping power for 0.33 Mev 10's. Parkinson, et al.,(Phys. Rev. 52, 75, 1937), have observed that the stopping power of aluminum decreases with decreasing energy in this region, and, while the amount of decrease they report is not sufficient to explain the discrepancy, values in this region of low velocity are sufficiently uncertain so that we do not feel that it is serious. Bennett (Proc. Roy. Soc. 155, 419, 1936) has measured for mica the variation of stopping power with velocity of the incident particles. His curves do not go to as low velocities as are involved in the 30 experiment, but extrapolation of the curves indicate a low stopping power.

The low stopping power of aluminum for low-energy 30's gave difficulty in the following manner: The thickness of the defining foil (1.0 air cm) was chosen thick enough to stop the 30 beam so that disintegrations could occur only in

the target region, and at the same time thin enough to permit the disintegration α's to reach the 0° collecting region. (All thicknesses of aluminum foil used in the disintegration chamber have been measured with 5 Mev alphas.) The first calculations, assuming 1.0 air cm, indicated that the α's would not penetrate the defining foil for incident energies up to 0.9 Mev. When the disintegration measurements were made, however, a very large number of disintegrations in the 0° collector were found at energies above about 0.7 Mev. This was very puzzling until the reduced stopping power of aluminum for low-energy α's was taken into consideration. The solution finally adopted for the high-energy measurements was to increase the thickness of the defining foil to 2.0 air cm.

2) Since the effect on the α ranges of the bombarding energy was underestimated, the original design of the disintegration chamber was such that α's emitted at large angles to the direction of the beam were counted by the 0° collector only for the highest bombarding energies. The effective solid angle for most of the energies was a function of the bombarding energy rather than being fixed by the collimating boundaries of the chamber. The data for the 0° collector are therefore taken under two different conditions. For mean energies between 0.5 and 1.0 Mev, a 2.0 air cm. defining foil was used. This thickness was necessary to stop the beam, although it limited the region of reliable data to high bombarding energies where the emitted α's have a

relatively long range. For incident energies between 0.2 and 0.65 Mev, a 1.0 cm defining foil was used. This permitted shorter range 240's to reach the collecting region and so permitted the use of lower bombarding energies. The intermediate region between 0.65 Mev and 0.8 Mev is strictly too low for the 2.0 cm foil since the 240's do not all have sufficient range to be detected and an appreciable correction is necessary. This correction, however, is neither too difficult nor too uncertain so that the information in this region was obtained from data taken with the thick foil.

3) Scattering of the incident 30's by the aluminum exit foil was found at the beginning when a check with 10 gas as the target was made. Appreciable numbers of pulses were observed with the 90° collector but not with the 0° collector. By substituting He and N_2 (at reduced pressure) it was shown that the effect was independent of the target gas, since the pressure of each gas was adjusted to give the same air equivalent as the 10 gas. The chamber was therefore dismantled and a shield inserted to hide the exit foil from the 90° collector and no pulses were then observed. The effect of this change on the solid angle is discussed later. At incident energies approaching 1.0 Mev, particles are again observed in the 90° collector when 10 gas is used. This is ascribed to particles scattered from the defining foil. Since this effect in the altered chamber was never more than twice normal background (about 10 per minute), no attempt has been made to eliminate it, but rather the effect

is measured and subtracted in computing the 90° cross section at the higher incident energies.

I-E. Energy Measurements. The direct measurement of the incident energy of the 30's was done in the same manner as described in the 230 report. Briefly, this method consisted in comparing the pulse-heights produced by the 30's and by polonium alphas passing into the N_2 filled target chamber.@ For this method to be valid, it is necessary that the 30's lose all their energy in the target chamber. The ranges of the 30's is such that this condition could not hold for all particle energies involved in the 30 experiment. It was thought at first that an N_2 pressure of 85 cm of Hg would make the target chamber thick enough to stop all particles up to 1.0 Mev incident energy. A consideration of the observed spread in incident energy* showed that the maximum energy loss that could be expected would be about 0.1 Mev less than that expected for a homogeneous beam. The maximum energy loss observed was actually about 0.8 Mev and the difference seemed outside experimental error.

The calculated energy losses given in the preceding paragraph were based on the proton data of the Wisconsin group. A range-energy relation based on the stopping cross section of oxygen as given by Ashkin and Bethe (Report LA 12)

@It was found desirable to use a lower nitrogen pressure for the determination of the alpha-particle pulse height so that the energy loss of the alphas and 30's would be more nearly equal. This procedure was found to be valid as long as the ratio of collecting voltage to pressure was constant.

*See Fig.3

leads to a calculated maximum energy loss of 0.9 Mev for a homogeneous beam of 30's, or about 0.8 Mev for the inhomogeneous beam, which is in agreement with experiment.

Since the direct measurement of incident energies was not possible above 0.8 Mev because of the finite chamber depth nor below 0.4 Mev because of the noise background of the amplifier, some other method was necessary for extending the energy determinations to include about 0.2 Mev and 1.0 Mev. Attempts were made to use CO_2 and propane for the higher energies since these gases have stopping powers greater than nitrogen, but they were not suitable because of lack of knowledge of their stopping power for low velocities and because of their poor characteristics as ionization chamber gases.

For each set of energy measurements made with nitrogen in the interval between 0.4 and 0.8 Mev, it was found that the energy was a linear function of (sec θ - 1), where θ is the angle between the normal to the plane of the secant foil and the direction of the beam. This relation is to be expected if the curvature in the relevant part of the range-energy relation is small. It was assumed that the curvature remained small outside of the region of directly measured energies and this linear relation was used for short extrapolation of the nitrogen measurements. The incident energy can then be written:

$$E = E_0 - K(\sec \theta - 1), \qquad (1)$$

where E_0 is an empirical constant and represents the energy of the beam entering the target chamber with the foil per-

pendicular to the beam, K is a constant depending on the thickness and stopping power of the foil, θ is the angle between the normal to the plane of the foil and the direction of the beam, and E is the energy of the beam entering the target chamber corresponding to any angle θ.

K, which is the slope of the E vs. (sec θ - 1) curve, was found to have the same value, 3.1, for all runs. E_o, the energy-axis intercept, was found to vary from day to day, as one would expect, since it depends upon the energy of the 30's as they leave the cyclotron dees. This emergent energy is a function of the cyclotron adjustments. It was possible, however, to establish a relation between E_o and θ_m, the angle corresponding to maximum relative ionization in 10 gas, by plotting E_o against (sec θ_m - 1), where E_o and θ_m for each point are determined from the same run. The uncertainty of setting the foil angle was about 0.5 degree, and within this uncertainty, E_o is a linear function of (sec θ_m - 1). This relation was used to establish the spacing of the curves in Fig. 4. In this figure, the incident energy is shown as a function of (sec θ - 1), giving a family of parallel straight lines, each line corresponding to a particular θ_m. In order to find the incident energy for any foil setting, θ, it is only necessary to follow the line (appropriate to the θ_m existing during that part of the experiment) to the value of (sec θ - 1). For convenience, the angles are also shown. It should be noted that the angles given are those read directly from the protractor and are denoted by "F". The

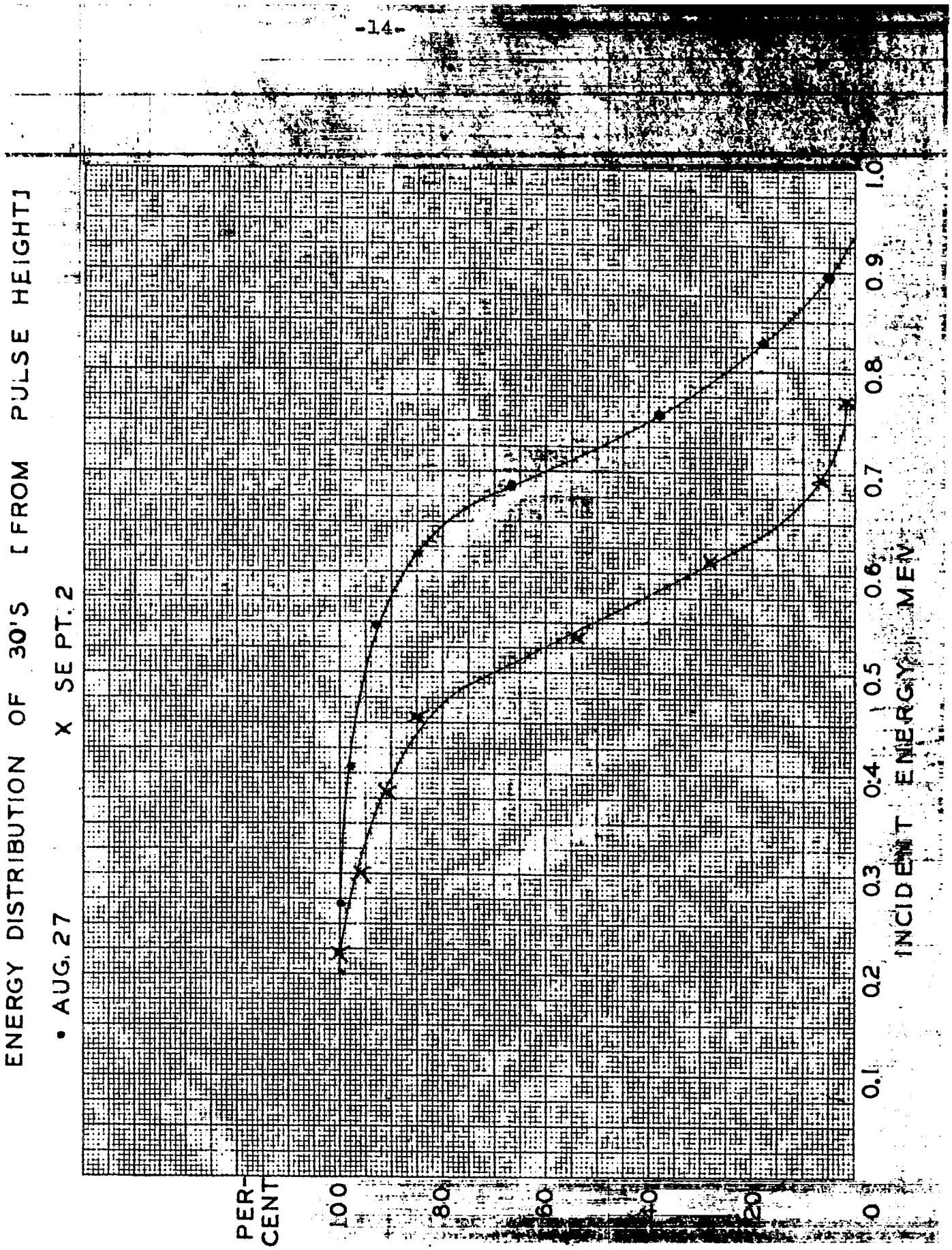


FIG. 3

INCIDENT ENERGY VS. FOIL SETTING

FIG. 4

ENERGY MEV

FOIL MAXIMUM

FOIL POSITION = F, θ = F + 3.75°

SEC θ − 1

0.024 0.048 0.072 0.096 0.120 0.144 0.168 0.192 0.216

3.75° 6° 8.2° 10° 12° 15° 17° 18° 19° 20° 21° 22° 23° 24° 25° 26° 27° 28° 29° 30° 31° 32°

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protractor angle for $\theta = 0$ is -3.75°, so $\theta = P + 3.75^{\circ}$.

All energy values used in connection with the relative ionization curves and disintegration data are obtained from the curves in Fig. 4. It should be realized that this energy scale is a smoothed-out scale based upon the average of many determinations of θ_m and E_0. Fundamentally, all energy measurements go back to direct comparisons of 30 and alpha particle pulse-heights with a N_2 filled chamber.

The energy scale of Fig. 4 is used to extend the range of energy determinations beyond the limits set by amplifier noise and the finite depth of the target region. It is obviously an extrapolation, but since it was not extended much beyond the directly measured region, it is felt that its accuracy is sufficiently good to warrant its use.

After the establishment of the energy scale shown in Fig. 4, it was possible to determine rapidly the energy of the 30's during any part of a disintegration experiment. This was particularly useful because of the energy drifts that sometimes occured during the course of a long run.

I-F. Pliotron Calibration. The beam of incident 30's was measured with a pliotron by the same method used in the 230 experiment (230 Report, pp. 11, 12,14,15). A change in the method of pliotron calibration was necessitated by the small energy loss (about 0.25 Mev maximum) of the 30's in the target region. Because of this small energy loss, a 30 beam small enough to be counted on the

pulse amplifier would not produce sufficient ionization to permit accurate readings of the microammeter connected to the pliotron. Accordingly, a movable screen technique was used in spite of the fact that a somewhat similar technique had given trouble during the 230 experiment.

Because of the trouble previously experienced, careful checks were made on the technique used in the present work. The movable screen used in the 230 work consisted of a series of slits formed by milled brass knife-edges. It was found that the transmission of this screen was very sensitive to its orientation with respect to the beam. Hence the position of the screen had to be determined very accurately. In the 30 work, the movable screen which was used was formed by rolling a fine-mesh brass screen to reduce its transmission to about 0.07. The transmission of this screen was found to be quite insensitive to small rotations. A number of measurements of the screen transmission were made during the course of the work under the same conditions under which the screen was used in the experiment. These measurements were quite consistent, the extreme spread in values being seven percent. No evidence of a change in the screen transmission with changes in cyclotron operating conditions was found, such a change having been the first symptom of trouble in the 230 experiments.

During the pliotron calibration, the beam was decreased to a suitable value by means of screens A and B, Fig. 1. Screen B was left fixed throughout the measurement while

screen A was movable. The number of counts in thirty seconds was taken with the pulse amplifier with screen A in place. This screen was then removed and the ionization current measured with the pliotron. This was repeated a number of times to average out fluctuations in beam intensity.

To increase the magnitude and therefore the accuracy of the reading of the pliotron meter for this measurement, a high counting rate was used on the pulse amplifier. Some of the particles were not counted at this rate because of the resolving time of the amplifier. That this was happening could be observed directly since at high counting rates a small group of somewhat larger pulses appeared due to the arrival of two or more particles in the chamber within the resolving time of the amplifier. These coincidences, or "doubles", were counted with the second output channel adjusted to detect only large pulses and the number of these large pulses was added to the number of small pulses observed. This correction amounted to about 2%. Before each pliotron calibration, the distribution in size of pulses counted was measured in order to be sure that there was no appreciable number of small pulses which might not be counted during the calibration measurement. A number-bias curve was obtained and extrapolated to zero pulse height, and the number obtained in the calibration increased by the ratio of the extrapolated value to the value used as a standard. This procedure indicated that, due to the small pulse size of the 30's, the pliotron calibration could be carried out directly only

when there was a maximum energy loss in the target region, i.e., at θ_m or "foil maximum". At foil maximum, the extrapolation indicated a loss in counts at the standard bias amounting to from 0.5 to 3 % and a correction for this was made in the pliotron calculations.

Since it was possible to calibrate directly the pliotron only at the energy corresponding to maximum energy loss in the target chamber, some method of extending the calibration to other energies was needed. In order to do this it was necessary to know the ionization produced by a constant number of 30's in the chamber as a function of the incident energy. This information was obtained by measuring with an exchange technique the ionization current for various secant foil settings relative to the maximum ionization current. At least one relative ionization curve was taken during each run. Several such curves are shown in Fig. 5. The energy axis of this figure is based upon the energy scale given in Fig. 4. The relative ionization curve is used in the extension of the pliotron calibration in the following manner: The pliotron calibration is defined as the ratio of the number of particles to the ionization current observed, and therefore the pliotron calibration is inversely proportional to the relative ionization current given by the curves in Fig. 5. Hence,

$$P/P_o = I_o/I \quad , \quad \text{or} \quad P = P_o I_o/I \quad , \qquad (2)$$

where P_o and I_o are the direct pliotron calibration and

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TYPICAL RELATIVE IONIZATION CURVES

○ Aug. 26, Before Run Normalized
× Aug. 26, After Run
▽ Sept. 2
• Sept. 3, Before Run Normalized
+ Sept. 3, After Run

8
7
6
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1.0

relative ionization current at the foil maximum, and P and I are the corresponding quantities at any other energy.

The relative ionization curves, in addition to being used to obtain the pliotron calibrations, were used to calculate the energy loss in the target chamber. With a constant number of particles entering the target region, the ionization current which they produce is proportional to their average energy loss in that region. In order to establish the absolute value of the energy loss, all the relative ionization curves were fitted to the curve computed from the report of Ashkin and Bethe at an incident energy of 0.95 Mev. This energy, the highest at which all relative ionization curves were established, was chosen since the accuracy of the theoretical curve is probably greatest at high energy and the curves to be matched are flattest in that region so any error due to a change in energy distribution is a minimum.

The values of the average energy loss were used to obtain the average energy of the beam in the target region. All cross section measurements have been quoted in terms of an average energy, $(\bar{E})_A$, obtained by subtracting one-half the average energy loss from the median incident energy.

The use of the relative ionization curve in both the pliotron calibrations and the calculation of average energy loss assumes that the number of particles entering the chamber is constant. Due to the spread in energy, this might not be true at low incident energies. A consideration

of the observed energy distribution shows that, except at the lowest energy used (0.29 Mev incident), no particles were lost and that here the loss amounts to only one or two percent.

The fact that the peaks of the ionization current curves of Fig. 5 occur at an energy of 0.46 Mev is of some interest. This is, of course, the value of the energy incident on the chamber for which the average energy loss is a maximum. The relationship between average energy loss and incident energy was calculated from the range-energy relation for protons of Ashkin and Bethe (Report LA-12) and showed a maximum at 0.38 Mev. This calculation took into account the depth of the chamber and the observed energy distribution. The value of the energy of 0.46 Mev is taken from the energy scale of Fig. 4 which is based on the average of a number of measurements. Since the energy determinations in this region are made directly and not extrapolated and since the individual energy measurements had a spread of only 0.02 Mev, it seems unlikely that the discrepancy between the calculated and observed values can be due to experimental error.

I-G. Experimental Procedure. The following is typical of the procedure followed in making a run: (In some cases, 12 and 13 were done prior to the 20 gas filling in 2.)

1. Turn on the pulse amplifier, pliotron and cyclotron; locate beam and let run for 30-45 minutes.

2. With 20 in ionization chamber, tune magnet to obtain maximum ionization on pliotron at maximum energy, ($\theta = 0$). Hold magnetic field constant.

3. Locate maximum foil setting by varying θ and observing pliotron reading.

4. Repeat 2 and 3 in about five minutes to check on drift. If little or no drift, proceed as follows; otherwise continue warming up.

5. Take a relative ionization curve, repeating series several times.

6. Make a pliotron calibration. (Section I-F)

7. Check on foil maximum and field maximum.

8. Take disintegration data. Foil settings are chosen to give about 100 Kv intervals between successive series. On each foil setting, sufficient counts are taken to leave at least 400 after subtracting background. Pliotron meter is read every 10 seconds and averaged later. Magnetic field is held as constant as possible. The field maximum and foil maximum are checked at frequent intervals.

9. A final check on foil maximum is taken and/or a complete relative ionization curve is taken.

10. Repeat pliotron calibration. (Not always done.)

11. Sample of 20 gas taken; chamber evacuated.

12. Chamber filled with N_2 and number-bias curve of 30's taken for foil settings used in step 8 above.

13. Polonium alpha source put in and number-bias curve taken. Arc is shut off, but magnetic field held constant for this measurement.

14. The chamber may be filled with 10 gas and a check run taken.

II-A. Solid Angle Calculations and Corrections. The solid angle calculations and estimations follow closely those given in the 230 report. Inasmuch as a smaller defining cone was used for the observation in the 0° direction than in the 230 case, it was necessary to recalculate the solid angle. The results of this calculation are shown in Fig. 6, in which the solid angle for each of the four levels is given as a function of the energy in the center of that level. The curve labeled $\bar{w}$ is merely the average of the solid angles of the four levels and, as such, is a good approximation to the average solid angle of the collimating system about the target chamber. When the chamber resolution and beam distribution are taken into account, the solid angles for the individual levels must be considered.

For low energies, the disintegration particles going out at angles near the maximum angle allowed by the collimator cannot reach the detecting region with sufficient energy to be detected. Obviously in these cases the solid angle actually existing in the experiment is smaller than that given by the curves in Fig. 6. Estimates of the corrections necessary because of the short ranges of the disintegration particles have been made in the following manner: An approximation to the observed distribution was used in which the distribution was represented by five energy groups, and the energy of each group in the center of each level calculated. For each level and energy group, the maximum angle at which disintegration particles can reach the detecting region with

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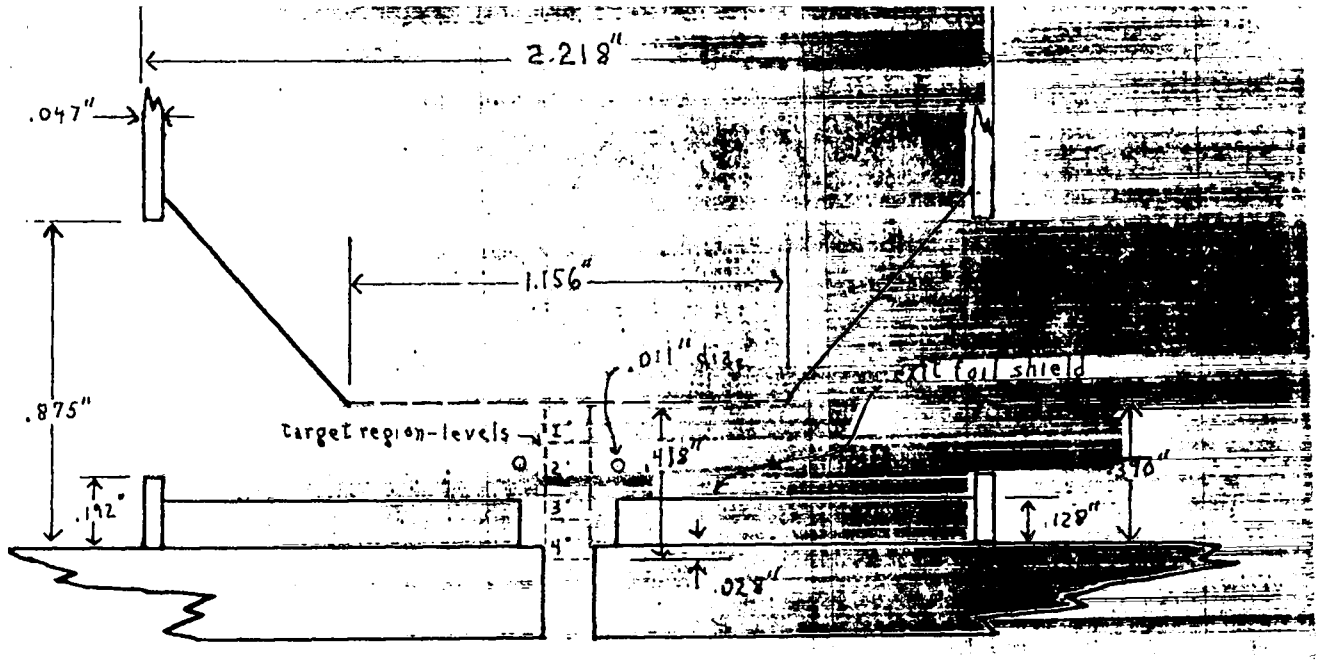
0.5 Mev was determined from the ranges of the disintegration particles and the distance in air cm from that level to the detecting region. When the solid angle in the laboratory system, calculated from such a maximum angle, was less than the solid angle given for zero energy (laboratory system) in Fig. 6, a correction factor equal to the ratio of the respective solid angles was applied for that level. The magnitude of the correction is discussed later in connection with the results.

There is one point in connection with this aspect of the problem which we do not as yet understand. Presumably, in those cases where some of the disintegration particles did not reach the 0° collector there were some which went only a short distance into the chamber and some which went entirely through the chamber. On the basis of an elementary analysis one would expect that in this situation there would be a continuum of pulse heights rising from zero pulse height to the maximum (occurring for particles which were emitted at just the right angle to allow them to end at the 0° collector plate.) This is somewhat at variance with the experimentally observed pulse height distributions which always had indications of a plateau. This makes us question somewhat the validity of the correction to the solid angle. We feel sure, however, that the number of disintegrations can be no less than the number observed, and that the solid angle is no larger than the value computed from the geometry so that the results represent at least a lower limit to the cross section. Since we can think of no measurements with

the cyclotron which would be conclusive on this point, and since only a more careful and extended calculation of the pulse height distribution to be expected can prove that the discrepancy is real, we do not feel justified in making a lengthy investigation at this time.

For observations in the 90° direction, all of the disintegration particles had enough energy to be detected. However, the calculation of the solid angles is made considerably harder by the introduction of the exit foil shield which was necessary to prevent 30's scattered from the exit foil from reaching the 90° collector. In view of the time that would be required to do this calculation in detail, it has been thought advisable to defer it until later. For the present, an estimate of the solid angle in the 90° direction has been used. The method of getting this estimate is the following: It can be seen from Fig. 7 that level 4 is almost entirely hidden from the 90° collimating system and it has been assumed that level 4 makes no contribution at all. About 16% of level 3 is blocked out by the additional collimator, which will reduce the effective number of target particles. It is assumed that the solid angle of the remaining portion is not much changed from that of the whole level by the small shift in effective position so that the previous calculations will apply (230 Report, p.22). Using the same solid angle curves as given in the 230 report for levels



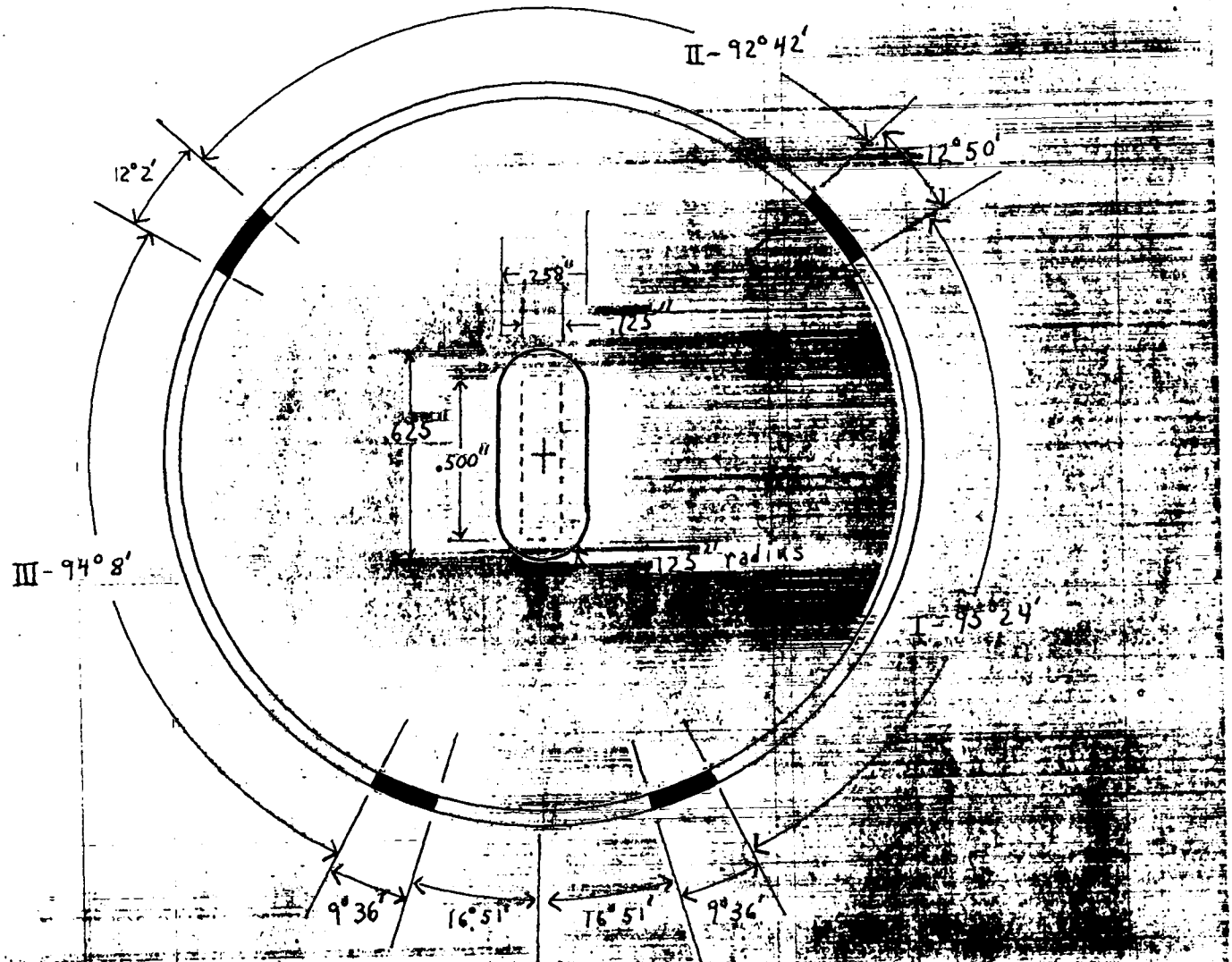


Fig. 7

DIMENSIONS OF 90° COLLIMATING SYSTEM

1, 2 and 3, the average solid angle curve in Fig. 8 is obtained. Since there is little change in this average solid angle with energy, the constant value of 0.109 has been taken for all energies. The value 0.109 is the fraction of the total 4π solid angle in the center of mass system with openings I, II and III forming the collimating system. However, opening II was blocked out with sheet copper for all 30 measurements because of the difficulty of shielding this opening from the exit foil. The solid angle was therefore decreased by the ratio of the areas of openings I and II to the sum of all three. This ratio is 0.661 and from this, the solid angle is 0.109 x 0.661 or 0.072. This value of the solid angle has been used in calculating the cross section as measured in the 90° direction.

Since none of level 4 and only 84% of level 3 is effective, the number of target particles involved in the disintegrations observed in the 90° direction is taken as 0.70 of that in the 0° direction.

II-B. Cross Sections. The cross section as observed in the 90° collector is shown in Fig. 9. The data taken on various days are indicated by the legend. The data taken on Aug. 21 makes the poorest set, both because the number of counts taken to determine any one point was small (about 280 at maximum) and because on that day experimental conditions were far from perfect. On Aug. 20, the experimental conditions were probably as poor, but about twice as many counts were

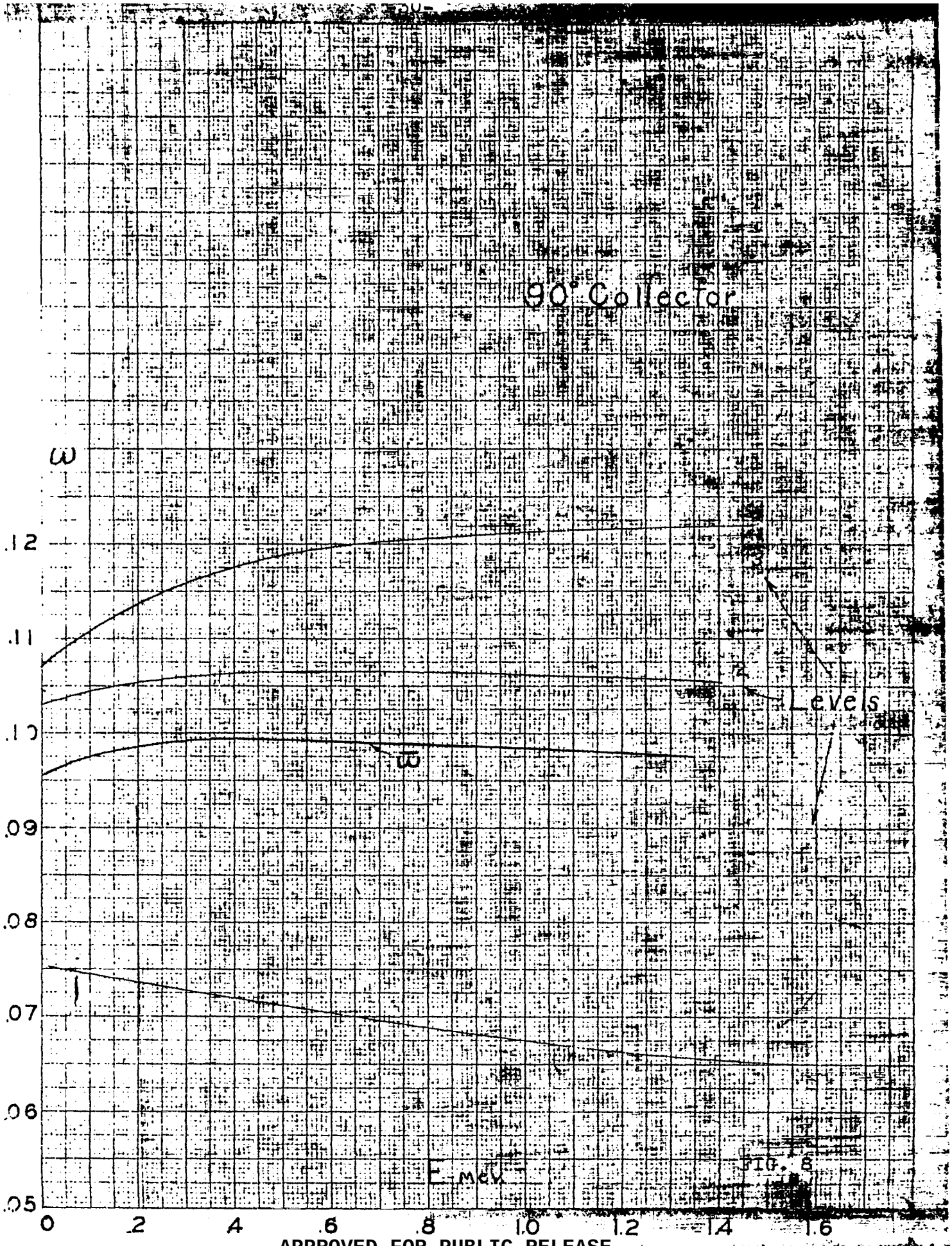
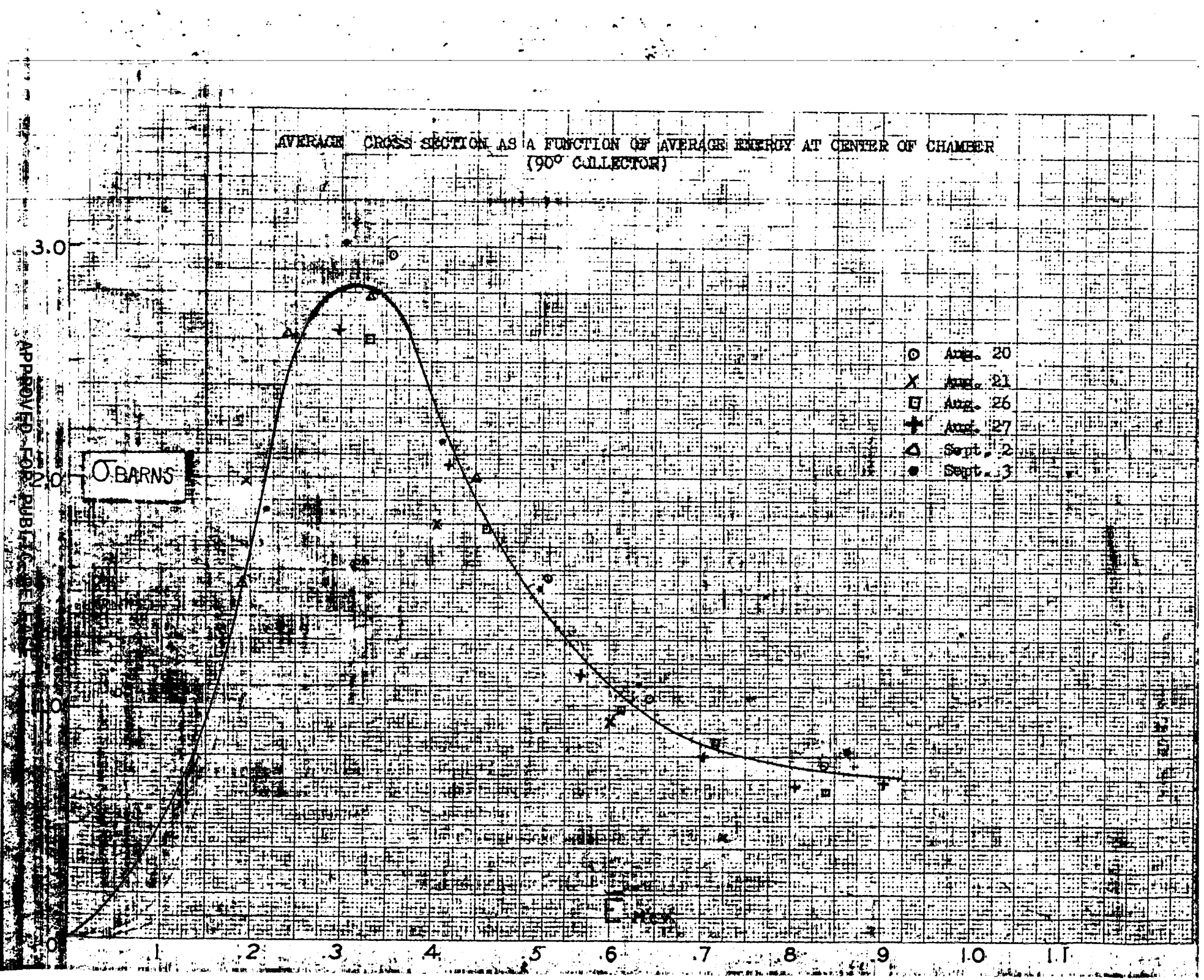


FIG. 8



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taken to determine each point. In particular, on these two days there was a drift in the energy throughout the runs and the only information available is the energy before and after the disintegration run. The reliability of the foil maximum method for determining energies was not realized at that time.

On the days Aug. 26 to Sept. 3, inclusive, frequent checking of the foil maximum allowed constant monitoring of the beam energy, and since by that time it was realized that the foil maximum gave a measure of beam energy, it was possible to keep the cyclotron tuned for optimum running conditions so that the beam was more steady than under the conditions of constant magnetic field.

The high energy points have been corrected for the background observed with 10 in the chamber, which we assume is due to scattered 30's from the defining foil. The correction for this background amounts to 22% at 0.93 Mev and decreases to zero at 0.73 Mev. No correction has been made at the lower energy points for the effect that might arise because the low energy components of the 30 beam do not get entirely through the target chamber. In view of the discrepancy between the observed relative ionization and that obtained by applying the known energy distribution to the specific ionization curve derived from the range-energy relation, it was thought inadvisable to go through the labor of making corrections based upon a range-energy relation which disagrees with these experiments. A rough estimate of the correction to be applied at an E of 0.2 Mev indicated that

the value of the cross section at that energy might be raised by about 10%. No correction has been made for the 1% gas impurity in our samples since the results of the mass-spectroscopic analysis have not been received as yet. Corrections have been made for the presence in the chamber of non-hydrogeneous gases, as determined by a chemical analysis.

In Fig. 10 is shown the cross section as determined by observation in the 0° direction. The statements made above concerning the quality of the work on the various days apply also to this curve since measurements were made both at 0° and 90° during each day's run. As can be seen from the legend, most of the high energy data were taken previous to Sept. 2 and with the thick (2 air cm.) aluminum defining foil. At all energies exept the highest, the thick foil prevented some of the disintegration particles from reaching the detecting region. As a consequency of this, all of the thick foil data were corrected for the decrease in solid angle with decreasing energy, and the points plotted for the days previous to Sept. 2 include this correction. The dotted line below the solid curve shows where the curve would have been drawn without this correction. This correction for the short-range disintegration particles was based on the assumption that all particles losing more than 0.5 Mev in the 0° detecting region will be counted above noise. The correction is probably good to 20% which gives rise to an additional uncertainty in the location of the points of not more than 8%.

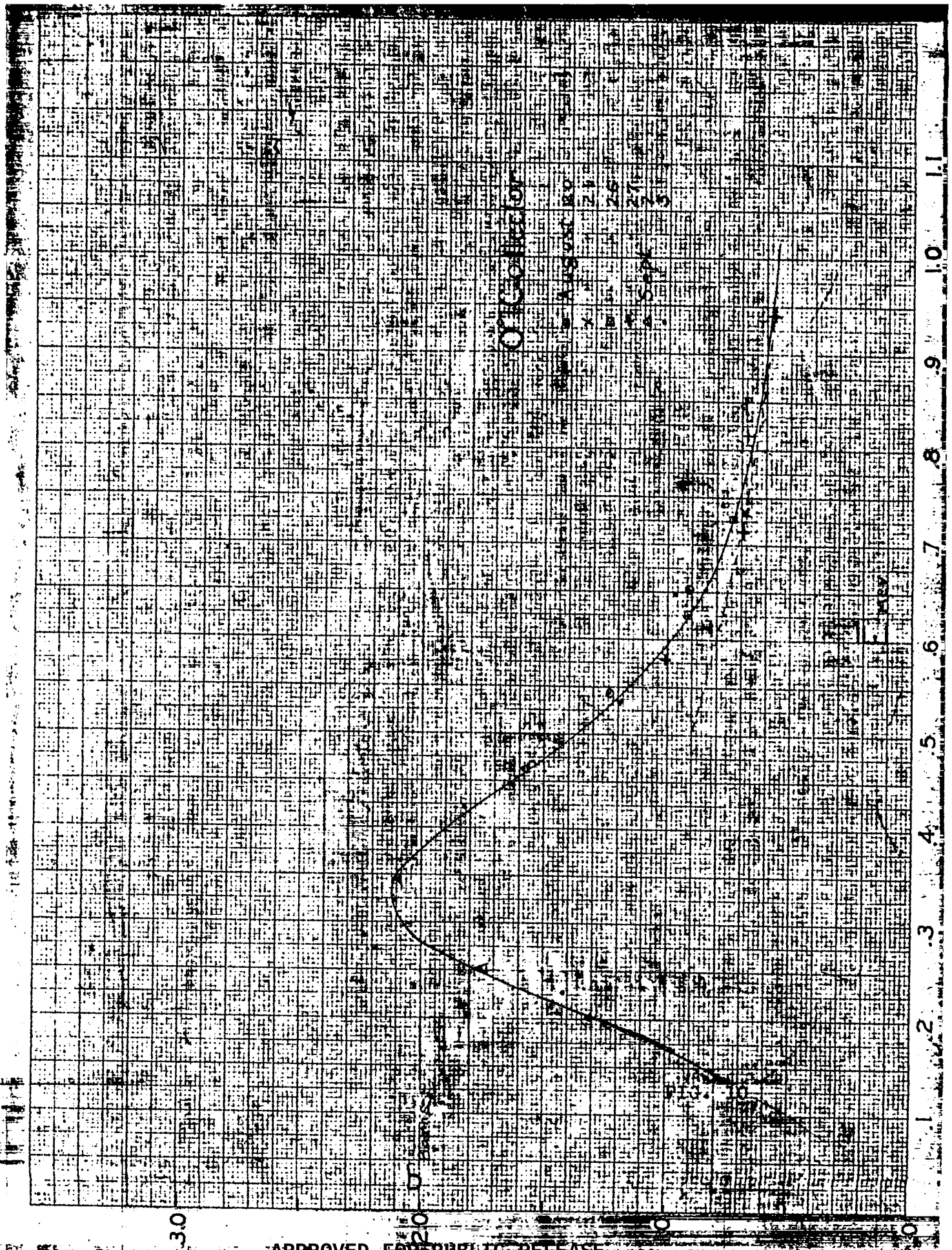

Fig. 10

On Sept. 2 and 3, observations were made with a thin defining foil (1 air cm) and the correction arising from the short-range disintegration particles is not very large, amounting to only 9% at an energy as low as 0.25 Mev. Since the correction was small and should be done more exactly at a later time, the data for the days of Sept. 2 and 3 have not been corrected for the effect of the short range disintegration particles.

The data shown in both Fig. 9 and Fig. 10 have not been corrected for the slope of the number-bias curve of disintegration particles. For the data taken at 90° this was not necessary since the distribution in pulse height showed that essentially all of the particles were counted at the standard bias. This was not true for the data taken in the forward direction, where the number-bias curves were not as flat and where we have good reason to believe that some of the particles are not being counted. While it would be possible to extrapolate the number-bias curves to zero pulse height and obtain a sort of correction, the interpretation of the values so obtained would necessarily be ambiguous. This extrapolation would be a guess at best and it is doubtful whether it would take into account all of the short-range particles. In certain cases with the 2.0 cm defining foil some of the particles do not reach the chamber at all and could hardly be accounted for in such a correction. It was thought better to calculate the cross section as determined at the standard bias used in the experiment, and then to determine what energy loss in the chamber was necessary to

give a countable pulse at the standard bias. From this it is possible (though laborious) to calculate the solid angle in which particles were actually observed and to correct the cross section accordingly.

The amount of energy loss represented by the standard bias was determined in two ways. The first was to calculate, in a favorable case, the number-bias curve expected in the 0^{o} chamber and to fit this to the number-bias curve actually observed. This was done twice and gave reasonable values of 0.53 and 0.57 Mev. The second method consisted of a direct measurement of the pulse height of polonium alphas in the 0^{o} collector using 10 gas. For this experiment, a polonium alpha source was placed behind the 0^{o} collector plate and the well-collimated beam of alpha particles entered the collector region through a small hole and traversed the collector region in a direction parallel to the axis of the chamber. A number-bias curve was taken with the pulse amplifier and the energy loss of the alphas was computed from the depth of the collector region and the filling data. The stopping power of the gas has been measured in a separate experiment and found to be 0.324 that of air for the full range of polonium alphas. The lowest bias which did not count appreciable noise corresponded to an energy of 0.33 Mev. Since this value is somewhat lower than that assumed in making the corrections for lost particles, the corrections may, in general, be a little too large.

The two cross section curves for the 90° and 0° observations are appreciably different. The 0° curve is consistently lower than the 90° one, the ratio being 0.83 at 0.9 Mev and 0.75 at 0.3 Mev, the energy for maximum cross section. There should be a correction for short-range particles of the order of four percent to the 0° curve in the region of the maximum so the ratio is probably nearer 0.78 than 0.75. The ratios at 0.9 Mev and 0.3 Mev are near enough to each other that one would be reluctant to say that the two curves differ by more than a constant factor. In view of the uncertainty in the value of the solid angle and number of target atoms used in the 90° calculations, the authors do not wish to discuss the possibility of anisotropy until the completion of the solid angle calculations and other corrections.

II-C. Errors and Uncertainty. Errors in the measurement of the cross section involve errors in (1) the number of disintegrations observed, (2) the number of target particles, (3) the number of incident particles, (4) the solid angle in which disintegrations were detected and (5), indirectly, the determination of the energy. An attempt will be made to assign to these quantities a "probable" error and an uncertainty. The error is our best estimate of the errors in the measurements, and the uncertainty is the limit within which we believe all errors lie.

For the various points in Figs. 9 and 10, the standard error arising from the statistical nature of the number of

disintegrations observed varied from 3 to 6% for all except the data of Aug. 20 and 21, for which the best established points have an error of 7% and the poorest 12 and 24%, respectively. It is probably safer to add 1% to this error due to the fact that the background rate may not have been entirely statistical but subject to wider fluctuations. At energies above 0.73 Mev, the background measured in hydrogen introduces an additional error, which might amount to 6% in the cross section at the highest energy and correspondingly less at lower energy. No correction was applied for the slope of the number bias curve in the 90° direction since it was not considered necessary. If any such correction had been applied, it could only have increased the number of disintegrations by about 1%. No corrections were applied in the 0° direction for the reasons discussed on page 35 of this report. It does not seem sensible to discuss what is meant by uncertainty in statistical measurements when the standard error is quoted. A reasonable value of the uncertainty in the corrections can be arrived at by doubling the errors for the fluctuation of background and possible slope of the number-bias curve, and trebling the error in the correction for the hydgrogen background.

The errors in the determination of the number of target particles are the same as those given in the 330 report in which an error of 1.1% was assigned, and the uncertainties due to the measurement of the physical depth of the chamber, the temperature and pressure measurements, and the determination of gas purity amounted to 4.5%, 0.5% and 1.0%, respectively.

The measurement of the number of incident particles was probably the most indirect of any of the quantities entering the calculation of the cross section. It involved: (a) the reading of the ionization current in the target chamber during the disintegration run, (b) the determination of the relative ionization curve used, (c) the determination at foil maximum of the relationship between the number of particles entering the chamber with screen A in place to the ionization current with screen A removed, (d) the measurement of the transmission of screen A, (e) the measurement of the ratio of the current sensitivity of the pliotron with a 10^{10} ohm input resistor used in (c) and with a 10^{9} ohm input resistor used in (a), and (f) the determination of the nonlinearity of the pliotron circuit.

The errors in (a) are considered negligible since the 30 beam was fairly constant and hence the average of the pliotron meter readings (taken every 10 seconds) gave a good approximation to the actual ionization currents.

From an examination of the constancy of shape of the relative ionization curves taken in various runs, the error involved in (b) is estimated to be 2% above an energy of 0.4 Mev and larger at lower energies, increasing to 5% at 0.25 Mev. The uncertainty is estimated to be 5% in the high energy range, increasing to 18% at the lowest energy.

One error in (c) is that arising from the fact that the ionization current and the counting rate were not measured simultaneously, but were taken alternately as rapidly as

possible. An estimate of 2% for this error was obtained by examining the individual ratios in each series of exchanges for internal consistency. This 2% also includes the error in reading the pliotron meter. In addition to the above error, there are two involved in the correction for the counts lost due to the finite resolving time of the amplifier and in the correction for the loss of small pulses. Since neither correction was large, the error introduced by them is taken as 1% and 2%, respectively.

Since the measurement of (c) is of a statistical nature, an uncertainty is difficult to assign. The only source of gross error could have been a sudden change in the characteristics of either the pliotron or amplifier, and since both instruments were in constant use, any such change, unless it were momentary, would almost surely have been detected. No evidence for any such behavior was ever seen. A very subjective estimate of the uncertainty is 7%.

(d) The transmission of screen A was measured five times by a comparison of the ionization current of the 30 beam with and without the screen. The extreme values were 1/12.2 and 1/13.1 with an average value of 1/12.6. The probable error estimated for each determination is 5% which gives a probable error in the average of 2%. This measurement was made with a somewhat larger beam than that used in (c) in order to increase the precision of the current readings. There is the unlikely possibility that the transmission was a function of the beam intensity, possibly because of some change in the characteristics of the ionization chamber with the amount of ionization current. Accordingly, one

measurement of the transmission was made coincident with measurement (c). Since the reading of the pliotron was painfully small, this measurement was of low precision but gave a value within 10% of the value measured at high beam which was within the estimated error of the measurement. The uncertainty in the measurement of the transmission of screen A was estimated to be within 10%.

The measurement of the ratio of the current sensitivities (e) was made three times during the course of the experiments. The maximum deviation from the average value was 5.7%. This is not as consistent a result as was obtained for the same measurement in connection with the 230 work. This may have been caused by changes in humidity which changed the leakage resistance and therefore the current sensitivity. On the other hand, since these measurements were interspersed with the disintegration experiments, the average value is a good representation in spite of the fluctuations. The probable error in this measurement is estimated to be 4% and the uncertainty 9%.

Measurement (f) is estimated to introduce an error of about 1.5% and has an uncertainty of 3%.

Since for measurements in the 90° direction the solid angle has not been finally calculated and since in the forward direction, because of the presence of short-range particles, the solid angle is an as yet unknown function of energy, no attempt will be made to assign errors to the determination of solid angle. The measurements of the dimensions of the

chamber were made with an error of 1 percent and with an uncertainty of 3 percent.

Except for the ratio of current sensitivities, the transmission of the screen and the determination of the nonlinearity of the pliotron, the measurements of the cross section on any one day are entirely independent of the measurements on other days. The value of the average energy to which the cross section measurements correspond is, however, taken from the compiled data of Fig. 4. The fact that the separate measurements are in agreement shows the small probability of large accidental errors. The transmission of the screen, the ratio of current sensitivities and the nonlinearity of the pliotron have also been measured a number of times previously under various circumstances with results not much different from the values used in this determination of the cross section, so that as far as the order of magnitude is concerned, the values of these three quantities have been established by a large number of measurements extending over a long period of time. The chance that these could be much in error is also small.

The error in the determination of the incident energy was estimated as 3.5 percent in the 230 report. This estimate was based on errors of 1.4 percent and 2 percent in the determination of the position of the curves of the distribution of pulse-heights for the polonium alphas and the 230's, respectively, and on an error of 1 percent in calculating the energy loss of the polonium alphas in the target chamber. In the 30 experiment the basis for the deter-

mination of an absolute energy scale depended on the same factors which were subject to the same errors. In addition, there is an error of about 20 Kv due to the experimental difficulty in setting the secant foil to better than 0.5 degree. However, since a large number of absolute energy measurements have been used to determine the secant foil curves of Fig. 4, the absolute energy values assigned to the cross section measurements are probably at least as good and possibly better than in the 230 measurements where each point on the curve was determined by but one energy measurement.

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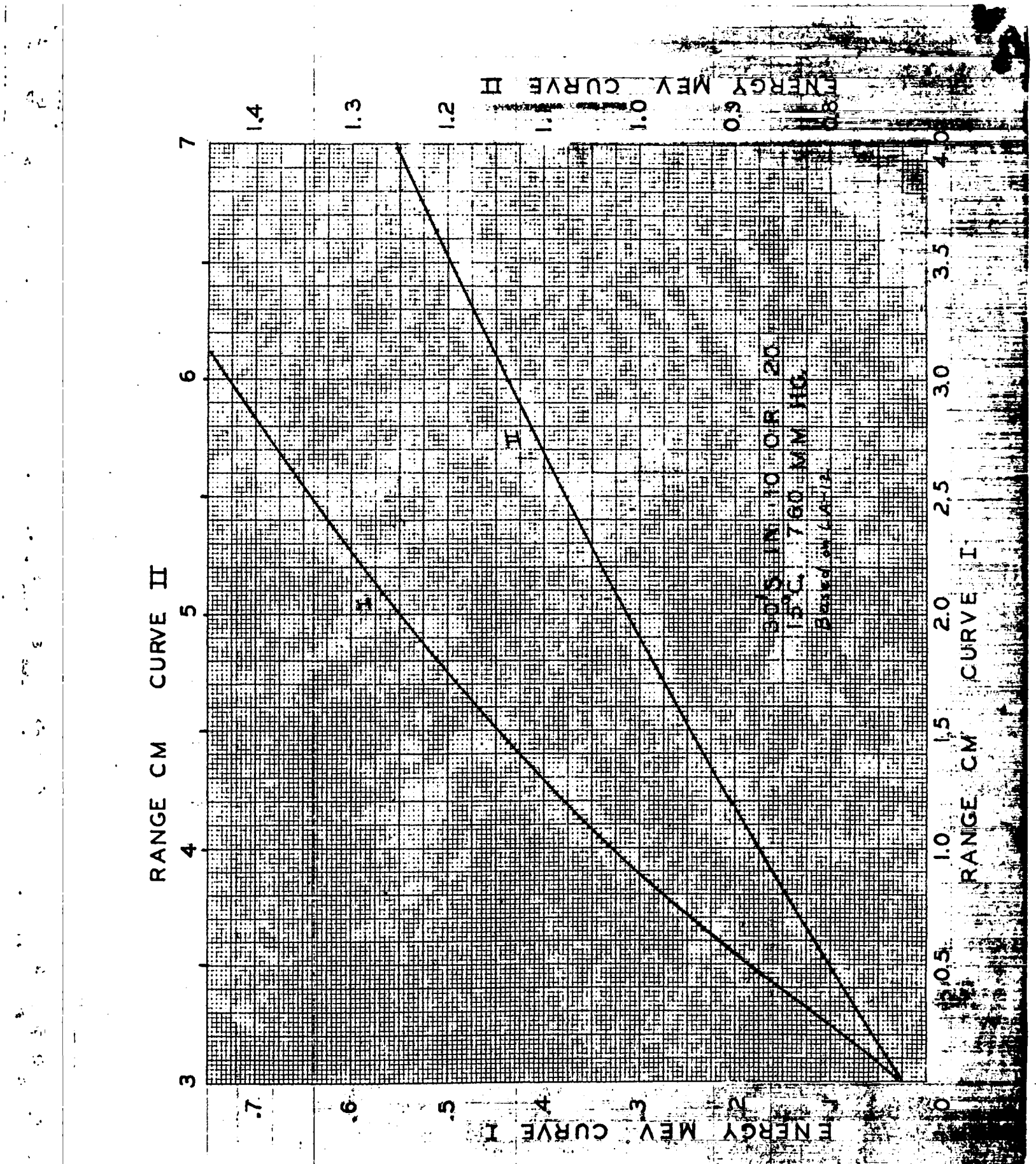

FIG. 11