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AN IMPROVED TECHNIQUE FOR TRACK PROFILE MEASUREMENT IN NUCLEAR EMULSIONS

by

James Edison Hall

M.S. Thesis, May, 1966

RELEASED FOR ANNOUNCEMENT

IN NUCLEAR SCIENCE ABSTRACTS

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AN IMPROVED TECHNIQUE FOR TRACK PROFILE MEASUREMENT IN NUCLEAR EMULSIONS

by

James Edison Hall

A Thesis Submitted to the

Graduate Faculty in Partial Fulfillment of

The Requirements for the Degree of

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In Charge of Major Work

Head of Major Department

Dean of Graduate College

Iowa State University
Of Science and Technology
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AN IMPROVED TECHNIQUE FOR TRACK PROFILE MEASUREMENT IN NUCLEAR EMULSIONS *

James Edison Hall

ABSTRACT

A microdensitometer utilizing a signal averaging digital computer has been developed to discriminate between the charges of particles producing short tracks in nuclear emulsions. It has been possible to average and store 1800 photoelectric profile signals per minute. For each track the photoelectric profiles of ten track segments, each 5.0 microns long, were averaged and stored by the computer, yielding a mean profile curve.

Results of measurements made on tracks produced by known particles of charges 1, 2, and 3 are presented. The normalized area of the profile curve was found to give the best charge separation. Measured photometric mean track width (MTW) values were corrected for the depth of the tracks in the emulsion. The charge groups were completely separated by measurment of 50 microns of each track, requiring less than 15 minutes per track.

* USAEC report IS-T-87. This work was performed under Contract W-7405-eng-82 with the Atomic Energy Commission.

I. INTRODUCTION

Nuclear research emulsions have been used for the purpose of particle track recording since 1927. They have proved to be a valuable tool of the high-energy physicist, enabling him to discover many elementary particles by observing the tracks they produce in nuclear research emulsions. A variety of methods has been used in an effort to make the most accurate determination of the mass and charge of a particle from its emulsion track. Charges of particles coming to rest in nuclear research emulsions have usually been calculated using the following methods (1):

(i) measurement of the frequency of δ-ray (secondary recoil electron) occurrence,

(ii) δ-ray cut off length measurement,

(iii) measurement of the number of gaps or developed grains per unit track length,

(iv) thin-down length measurement.

New electron-sensitive emulsions capable of registering tracks of particles at minimum ionization have been developed. The high sensitivity of these emulsions causes the more heavily ionizing particles to give tracks which are so dense that the individual grains overlap, making grain counting impossible. Methods (i) and (ii) are not suitable for analysis of tracks of particles of low charge because few δ-rays are observed. Thin-down length measurement is only applicable to particles with high Z. All of these methods require subjective judgments in the measurements.

In order to estimate the charge of particles stopping in highly sensitive emulsions, the widths of their tracks have been studied. The width of a track depends on the characteristics of the emulsion, the development the emulsion has received, as well as on the charge and velocity of the particle producing the track. Alvial et al. (2) have made an extensive study of track widths using eyepiece micrometers. They found it necessary to define carefully the conditions of measurement; for example, the intensity of the microscope light and the fatigue of the observer.

Although a measurement of the geometrical track width gives valuable information in many cases, a more objective measurement is desirable. Using the notation of Barkas (3), the photometric mean track width (MTW) is defined as follows. Consider viewing a track through a narrow slit which is parallel to the track and located above it. The track is illuminated by a light which shines upward through the bottom of the emulsion plate. Let the average intensity of the light transmitted on both sides of and near the track be denoted by I_o, and the intensity of light transmitted with the track image centered in the slit be I. For a slit much narrower than the width of the track, I is measured as a function of the displacement, y, of the center of the slit from the axis of the track. Then, the photometric mean track width is defined as

$$MTW = \int_{-y_o}^{y_o} \left[\frac{I_o - I}{I_o} \right] dy \quad , \qquad (1)$$

where y_o is the displacement at which $(I_o - I)$ falls to zero. Thus, MTW is a measure of the geometrical width and the density of developed grains of an emulsion track. Measurements of the MTW of a particle track were first made in 1950 (4) using a light-sensitive photomultiplier tube to determine the transmitted intensities. The particle variables of velocity and charge affect the MTW, and this connection can often be usefully exploited.

There are certain limitations to the method of photoelectric determination of MTW in its present state. The most common application of this method is to measure the MTW of small segments of a track and then to sum arithmetically the results for the whole track, necessitating many timeconsuming measurements. Existing techniques require a measurement of at least 100 microns of track length in order to produce reliable results. In emulsions which have been exposed to a separated K^- beam, in order to produce hyperfragment tracks, the range of the tracks of particles of charge greater than one is often less than 100 microns. A need for improvement of the photoelectric method and associated equipment so that MTW measurements may be made in less time, on shorter tracks, and with more accuracy is clearly indicated.

It is the purpose of this thesis to summarize the methods and instrumentation which have been used for photoelectric MTW measurements. New techniques are described with the associated instrumentation constructed to enable accurate measurements to be made of the MTW of particle tracks with range less than 100 microns. Measurements are given which were made on tracks produced by known particles in order to estimate the accuracy of the technique in determining the charge of the particle by measuring the MTW of its emulsion track.

II. PREVIOUS WORK

The photometric mean track width and the application of this quantity to the determination of a particle's mass and charge have been studied extensively by von Friesen and his collaborators in Lund. In the early 1950's von Friesen and Kristiansson (5), and Kristiansson (6) reported on the results of measurements they had made with a photoelectric instrument constructed for MTW determinations. A Leitz model BST 48 microscope was modified by replacing the body tube and eyepiece with a new section which contained a slit positioned in the image plane of the objective and a photomultiplier tube above the slit. The slit acted as a luminous object with a light density which was everywhere constant over the surface of the slit except in the region where silver grains in the emulsion gave an image in the slit; in this region it was zero. Light from the slit hit the cathode surface and gave an output current from the photomultiplier tube which decreased in proportion to the area of the slit screened by the track. With the track image centered in the slit, the photomultiplier current was measured. Measurements were also made on each side of the track and then averaged to give the background intensity.

The difference between the reading with the track image in the slit and the mean background reading was used as a measure of the grain density caused by the charged particle. The slit width was adjusted to correspond to 3 to 4 times the width of the track being measured. The length of the slit corresponded to 30 microns of track length. Measurements were made every 50 microns along the track and then arithmetically summed. It was found that by measuring 400 microns of track length π- and μ-mesons could be distinguished with certainty, but that it was not possible to separate protons, deuterons, and tritons.

Subsequent measurements using modified versions of this apparatus were reported by Waldeskog (7), Kristiansson (8), von Friesen (9), von Friesen and Stigmark (10), Kristiansson (11), and Waldeskog and Mathiesen (12). A plane-parallel glass plate was placed in the beam of light inside the microscope tube in order to switch easily from the track to the background. Rotating the plate slightly caused a displacement of the field of view in relation to the slit, allowing the three desired measurements to be made without movement of the emulsion plate. A pen recorder was substituted for the galvanometer as a means of recording the current from the photomultiplier tube.

Valuable information was obtained in many cases through the use of this apparatus, but it had two major drawbacks. First, to obtain a reliable measurement, at least about 500 microns of track length had to be measured, thus excluding the use of shorter tracks. Second, the many measurements required on each track demanded a large amount of time (about one hour for each 1400 microns measured).

Whereas von Friesen and Kristiansson had measured tracks in 200 micron thick electron-sensitive emulsions, Ceccarelli and Zorn (13) made measurements using 400 micron thick emulsions. Denoting the photomultiplier output current as R_t and R_b, corresponding to whether the track was in the field of view or not, they investigated the quantity

$$R = \frac{R_b - R_t}{R_b} \tag{2}$$

for different tracks. For thin emulsions R was found to be a consistent measure of track density, but for 400 micron thick emulsions the scattering of light by the emulsion during the measurement was found to present a problem. Ceccarelli and Zorn determined values of R at different points along a track which traversed the emulsion. Since the results suggested a marked decrease in the opacity of the track with increasing depth in the emulsion, they concluded that R could be taken as a true measure of track density only in a region very near the surface of the emulsion.

Unable to overcome this effect, Ceccarelli and Zorn adopted an alternate approach. Using a slit with a projected width of 0.25 microns in the plane of the emulsion, they moved the emulsion plate in a direction perpendicular to that of the track, taking galvanometer readings at regular intervals during this movement across the track. By plotting these readings as a function of displacement from the center of the track, curves of the form shown in Fig. 1 were obtained. The shape of the curve was found to be independent of both the ionization of the particle producing the track and the width of the slit if its image in the object plane was less than the mean diameter of a silver grain. The width of the curve at half amplitude ('half-width') was found by Ceccarelli and Zorn to be independent of the depth of the track in the emulsion, and, therefore, was taken as a measure of the ionization of the particle. Measurements were made of the half-width of the track at a succession of points 50 microns apart and the sum of the values thus obtained, called the 'integral half-width', was used to identify charged particles stopping in the emulsion.

Modifying the apparatus used at Lund, Johansson (14) found it possible to graph a profile curve of the track automatically. He rotated a plane-parallel glass plate in the beam of light by a small synchronous motor, thus sweeping the image of the track across the slit at a given frequency. The output of the photomultiplier was amplified and fed to a pen recorder using a paper speed of 1.5 mm/second. A typical trace is shown in Fig. 2. The area under the curve BCA, being a function of the number of grains in the track, is thus a measure of the ionization caused by the particle. Dividing this area by the length u makes the former independent of the light intensity and may be regarded as a measure of MTW[1]. Johansson verified that the area may be approximated by the product h (the height of the peak) and b (the

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[1]In practice the integral definition of MTW as given in Equation 1 is approximated by $\{b(I_o - I)/I_o\}$, where I is measured at the peak of $(I_o - I)$ versus y, and b is the half-width. Since absolute track widths depend on emulsion sensitivity and development, no fundamental significance can be attributed to the photometric mean track width. Thus, consistent use of the above approximation results in no loss in precision.

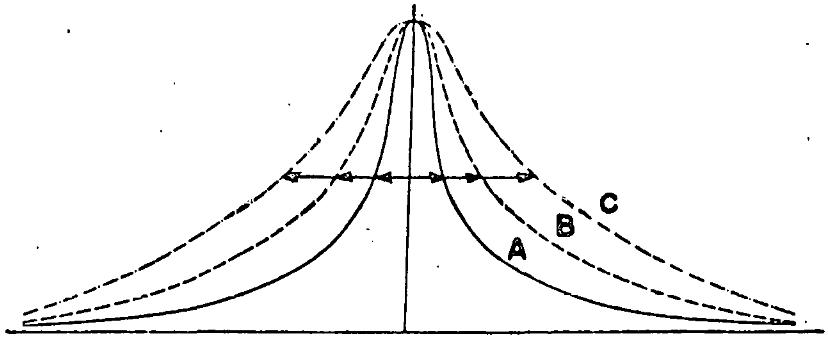


Fig. 1. Track profiles obtained by Ceccarelli and Zorn (13) for tracks of particles A, B, and C, with ionization loss of 350, 820, and 1400 MeV/g/cm^2, respectively

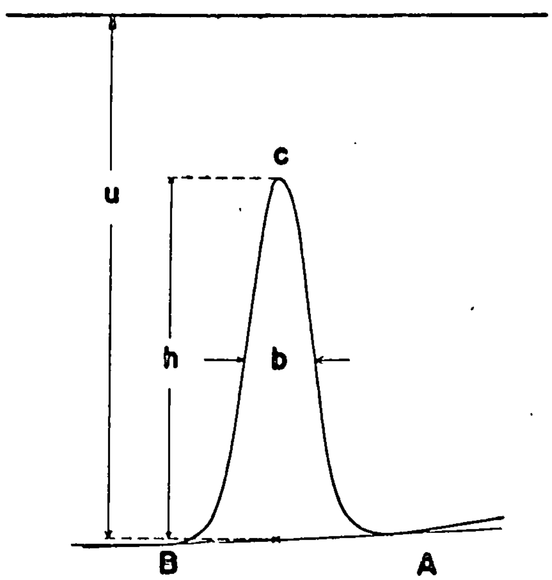


Fig. 2. Track profile obtained by Johansson (14) for a proton track

half-width). Then,

$$MTW = \frac{h \cdot b}{u} \quad . \tag{3}$$

Using a slit of dimensions 10 microns by 0.76 microns in the plane of the emulsion, he obtained a profile curve for each 10 microns of track length and then formed the sum $\sum_{0}^{R} MTW$ of the individual measurements. The summation was extended from R = 0 to R = 200, 100, and 50 microns. When measurements on tracks with residual range 200 microns were used, values of $\sum_{0}^{200} MTW$ for tracks of particles with Z = 1, 2, 3 were nicely divided into three groups, giving a complete separation between the different charges. Measurement of the last 100 microns of the same tracks again yielded a splitting into three different groups, although the separation was no longer a perfect one. If only the last 50 microns of track were used, separation of charge 1 and 2 with a reasonable degree of certainty was impossible.

The fact that the profile curve of a particle's emulsion track contains valuable information as to the identity of the particle is now well established, but there is a question of which is the most meaningful parameter, the area or half-width of the profile curve. Johansson (14) obtained good results measuring the area, but Ceccarelli and

Zorn (13) concluded that the half-width is the most meaningful because it is independent of a track's depth in the emulsion.

Evans and Hillier (15) made measurements of half-widths and found a depth dependence. By placing a slit in front of the light source, thus reducing the background illumination except in the immediate vicinity of the track, they were able to reduce this effect.

Using apparatus similar to that used by Johansson (14), Kenyon (16) measured both the half-width and the profile area for a group of tracks of known ions with Z = 1, 2, and 3. The slit he used had projected dimensions of 6.25 microns by 0.13 microns in the plane of the emulsion. Like Evans and Hillier, Kenyon placed a slit below the condenser lens in order to reduce the scattering of light. He found that a measurement of the profile area gave much better separation of the charge groups than did a measurement of the half-width. However, the tracks measured by Kenyon were all located at approximately the middle of each emulsion. Problems involving depth correction were thereby avoided.

Making profile measurements on 6.25 microns of track length at a time, Kenyon arithmetically summed the result of

10 and 20 measurements of each track. His results are shown in Figs. 3 and 4. There was good separation between charge groups if 127 microns of track length were measured, and fairly good separation maintained if only 62.5 microns were measured.

Although measurements were made only for the idealistic case of all tracks being located at the same depth, Kenyon's measurements are the most impressive reported to date. They indicate that with adequate depth correction it may be possible to confidently identify particle tracks less than 100 microns long by photometrically measuring the track profile. With the growing interest in the analysis of hyperfragment tracks, some rapid and reliable means of charge discrimination is essential. Improvement is still necessary in the time required for the complete measurement of a track.

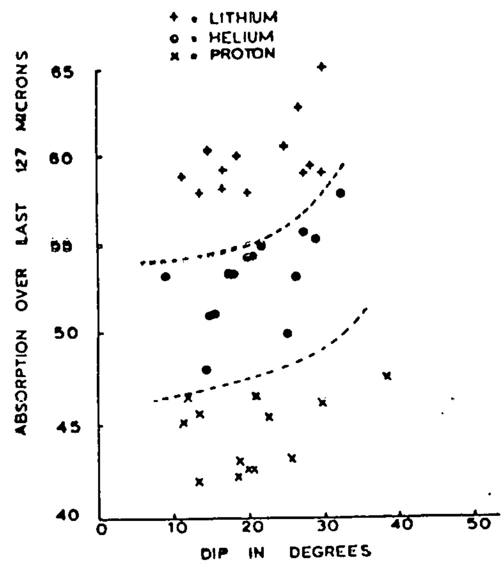


Fig. 3. Normalized profile measurements by Kenyon (16) of the last 127 microns of known tracks; each point represents one track

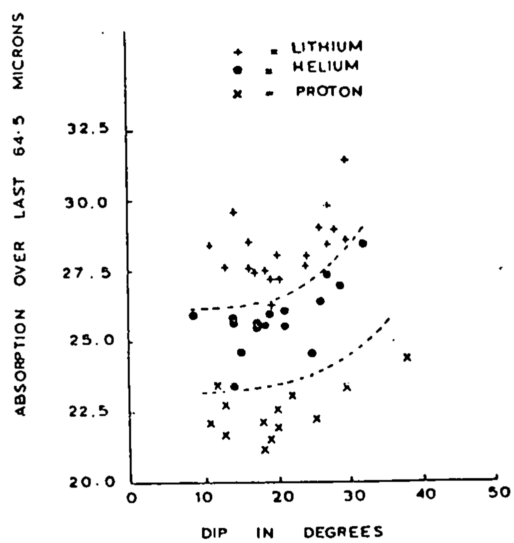


Fig. 4. Normalized profile measurements by Kenyon (16) of the last 64.5 microns of known tracks; each point represents one track

III. PRESENT TECHNIQUE

A. Method

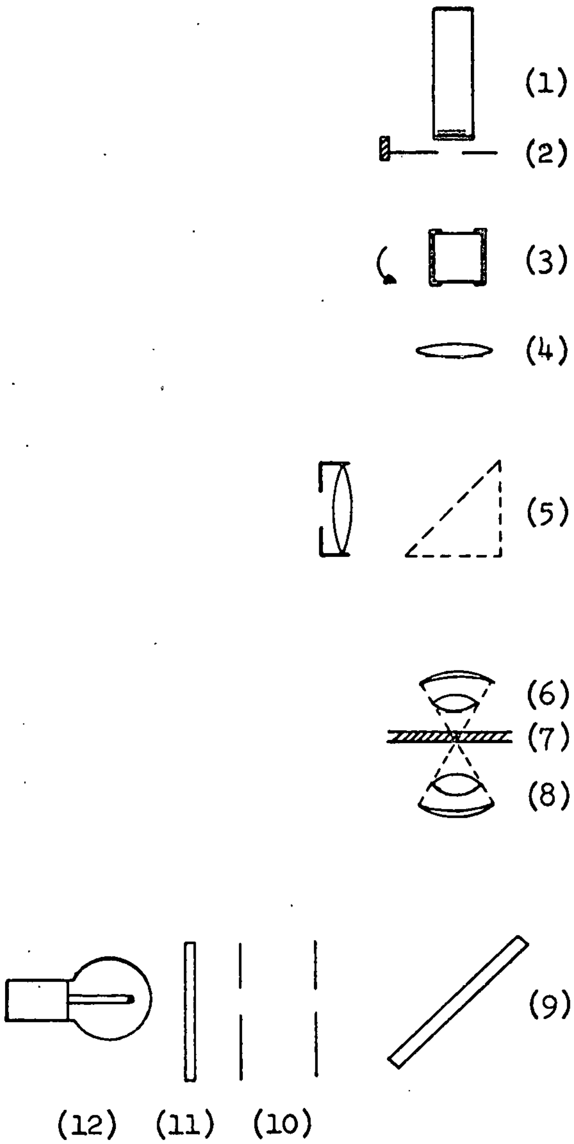
The major problem encountered in previous attempts of various investigators to obtain reliable measurements of the photometric mean track width was the inconsistency in the measurements due to fluctuations and noise in the instrumentation. Making a single measurement of the MTW of a portion of a track was not sufficient to allow the investigator to assume that the measurement yielded an accurate MTW value for that segment. However, if several measurements were made on each segment and the average value was found, an impractical amount of time was required for measuring a single track.

Previous methods required the calculation of MTW, either from a graph or an oscilloscope screen, after each sweep of the image of the track across the face of the photomultiplier tube. In the present investigation, equipment was utilized to allow the storage and averaging of MTW curves for individual segments along a track. The method allowed a large number of measurements to be electronically stored and averaged for a single segment of the track. Thus, after a complete track was scanned by the photomultiplier tube, a single MTW value was calculated, which was the average MTW for the whole track.

B. Apparatus

The optical details of the system utilized in the present investigation are shown in Fig. 5. The system was built into a Brower scattering microscope. Illumination of the emulsion plate was accomplished by the use of GE-855K 4-volt, 2.5 ampere bulb with a straight wire filament. In traversing the distance from the bulb to the emulsion, the light was slightly diffracted and the wave length-dependent photomultiplier tube did not consider the illumination uniform. A Wratten green filter (No. 61) was placed between the light source and the emulsion plate in an effort to provide uniform illumination of the track in the emulsion. This filter was chosen because its range of maximum transmission was 5000Å to 5600Å. An EMI 9524B photomultiplier tube with a lime soda glass end-window photo cathode of the S-11 type, which has maximum sensitivity in the 3500Å to 5700Å region, was used. Thus, an attempt was made to match the illumination frequency to the maximum sensitivity frequency of the photomultiplier.

In an effort to reduce the amount of light scattered in the emulsion, two field stops were inserted between the



(1) Photomultiplier

(2) Adjustable Slit

(3) Rotating Glass Cuboid

(4) X25 Eyepiece

(5) Eyepiece For Visual Inspection

(6) X100 Objective

(7) Emulsion

(8) X32 Objective (Inverted)

(9) Mirror

(10) Field Stops

(11) Filter

(12) Light Source

Fig. 5. Optical details of the microdensitometer

filter and the mirror which reflected the light beam through an angle of 90 degrees. The mirror was hinged at the top and by means of a fine adjusting screw was used to precisely position the band of light on the track. Light reflected from the mirror entered an inverted 32x objective which reduced the size of the light band to 2.5 microns in the plane of the emulsion. The vertical position of this objective was variable so that the light band could be focused at any desirable depth in the emulsion.

The track was viewed through interchangeable objectives, using a 100x while measuring. For location and alignment of tracks, the emulsion was viewed through the microscope eyepiece (located above the objective). By moving the prism which refracted the light through the eyepiece, the image of the track was allowed to pass up through the vertical tube to the photometer head. Two views of the microscope are shown in Fig. 6.

The photometer head was connected to the microscope body by a brass adapter, which contained a 25x eyepiece for further magnification. Thus, the image of the track had undergone a magnification of 2500 when it reached the photometer head. Positioned directly over the optical axis of

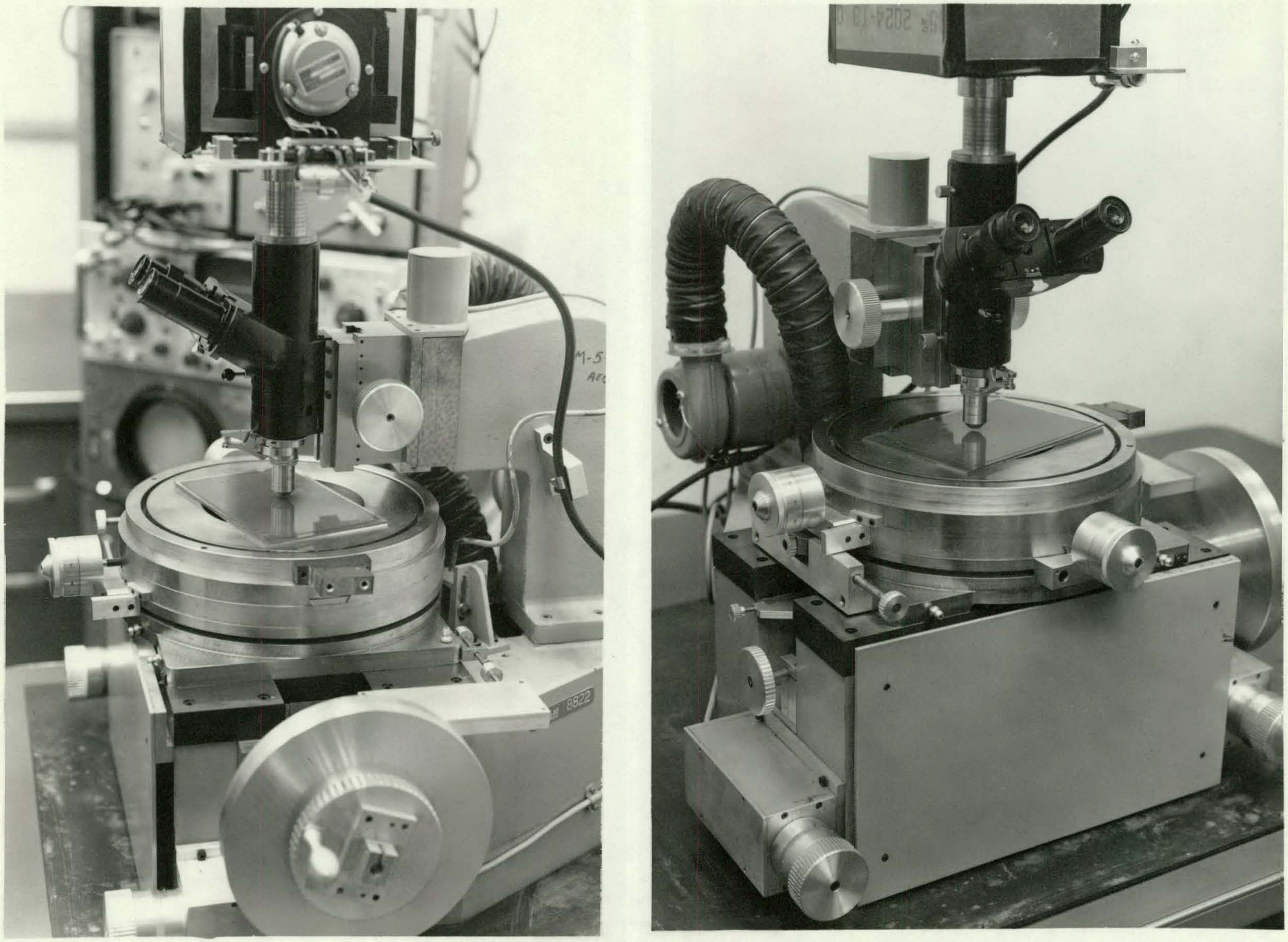


Fig. 6. Two views of the modified Brower microscope

the 25x eyepiece was a 1.0 cm. by 1.0 cm. by 5.0 cm. glass cuboid mounted on the shaft of a synchronous motor as shown in Fig. 7. Above and parallel to the cuboid an adjustable slit was mounted on a moveable lucite support. A slit width of 12.50 mm. by 0.30 mm. was used, corresponding to 5.0 microns by 0.12 microns in the plane of the emulsion. The EMI 9524B photomultiplier tube was attached to the top of the slit so that light passing through the slit fell on the photo cathode surface. As the cuboid rotated, the image of the track was swept across the slit. Two opposite faces of the cuboid were blackened so that there were two sweeps (in the same sense) per revolution. All of the photometer components except the synchronous motor were mounted in a light-tight aluminum box. The motor was mounted outside the box to insure good heat dissipation.

The electrical details of the system are shown in Fig. 8. A stabilized current supply was used to provide the power for the light source. Using a highly regulated power supply, a negative 1000 volts was applied to the photomultiplier tube. The signal from the photomultiplier was amplified by a transistor amplifier with gain variable between one and ten; the gain was always adjusted to provide an output signal of 0.35

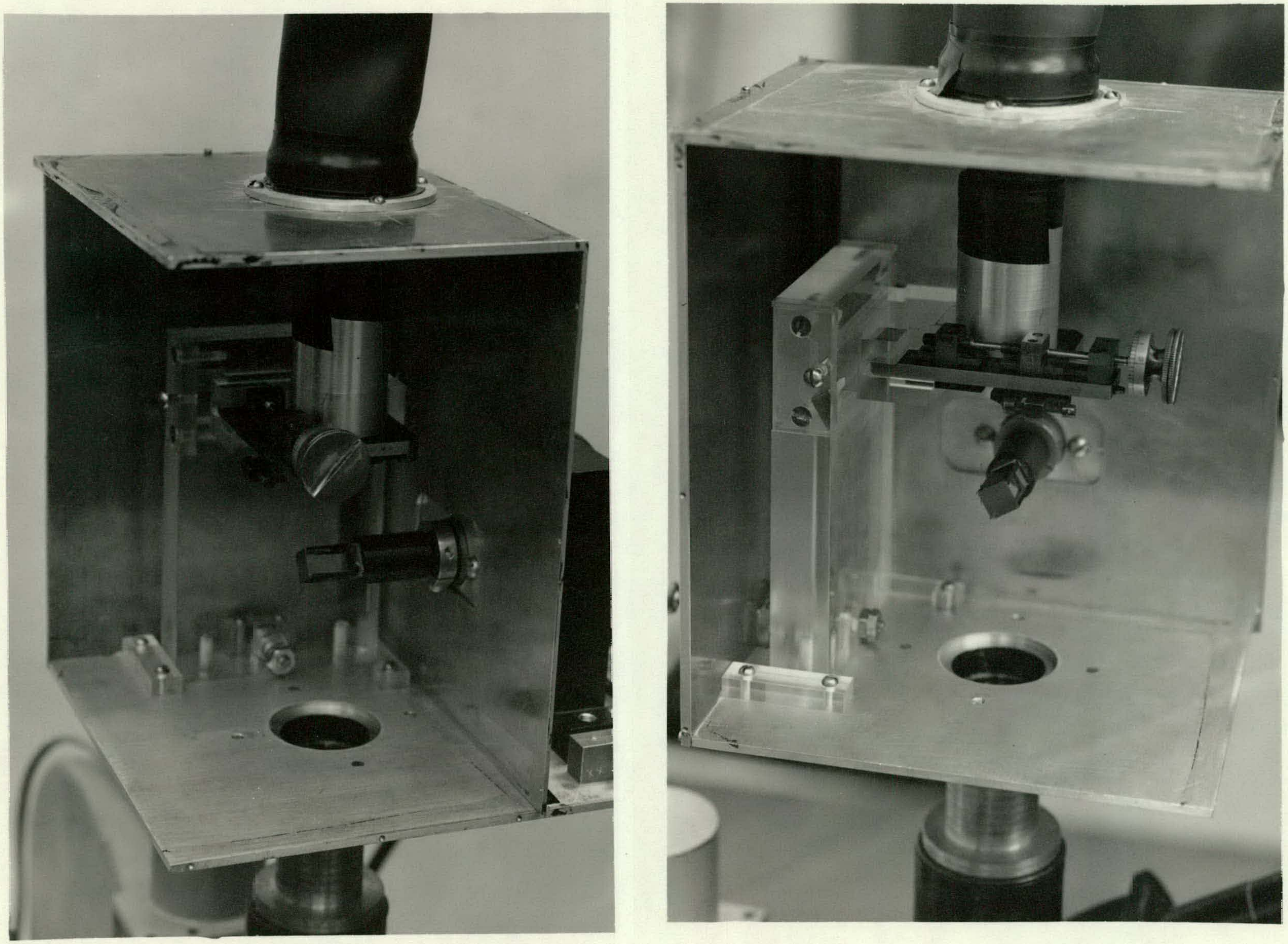


Fig. 7. Two views of the inside of the photometer head

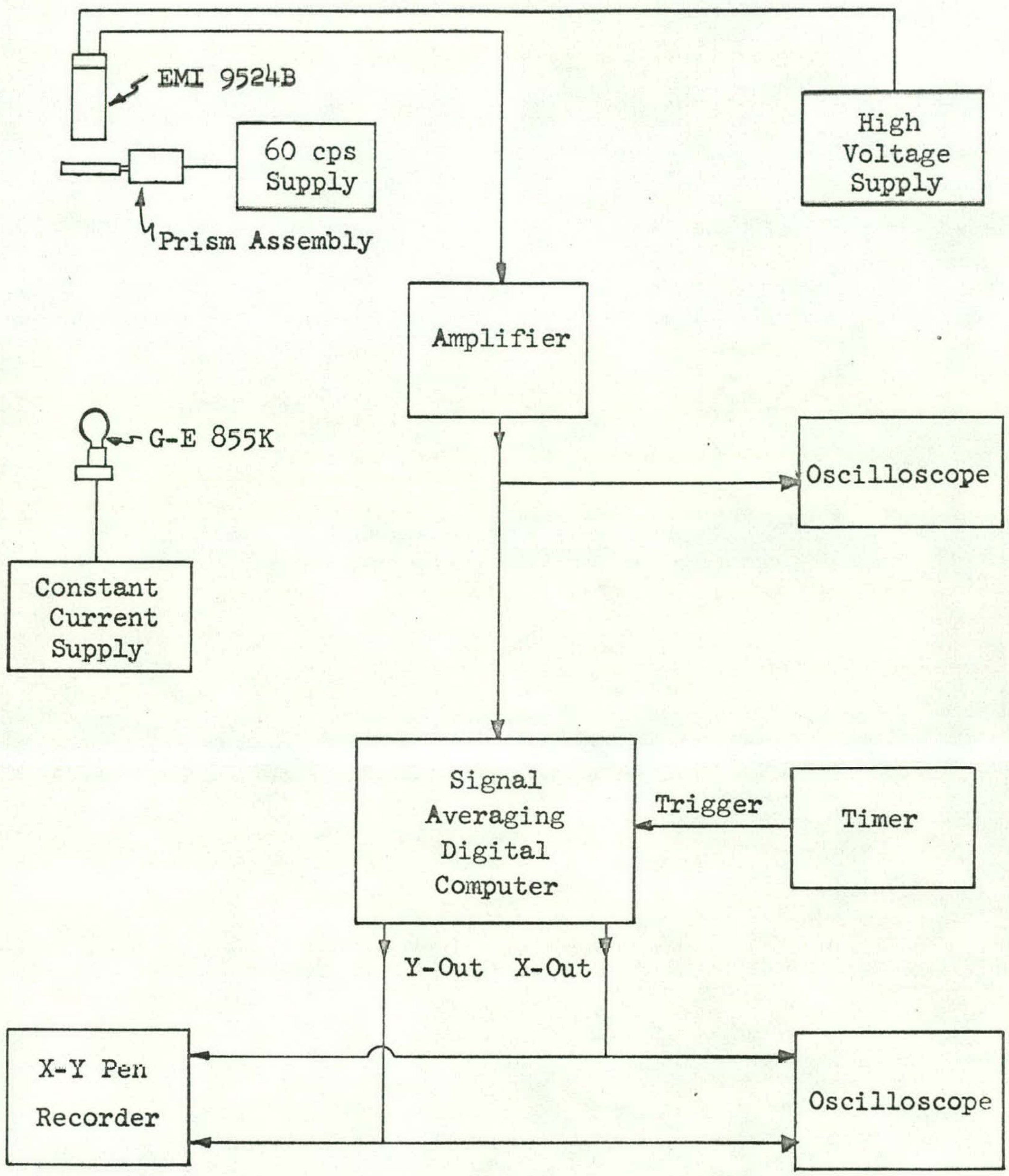


Fig. 8. Electrical details of the microdensitometer

volt peak-to-peak. The signal from the photomultiplier was noisy but fluctuated about some mean value, as shown in Fig. 9. This signal was put into a signal averaging digital computer[1] and at the same time displayed on an oscilloscope.

Connecting the four-pole synchronous motor to a voltage line of frequency 60 c.p.s. produced 1800 revolutions per minute and, hence, 3600 sweeps per minute. (This is the fastest rate at which the Enhancetron can accept input information.) Due to the inability to achieve perfect alignment in the optical system, the signals from the two possible orientations of the cuboid differed slightly in phase. Therefore, only one sweep per revolution could be used. After the Enhancetron averaged and stored each signal, it stopped and awaited a 10-volt trigger pulse before starting through its averaging cycle again. It was necessary to construct a timing system which produced the necessary trigger pulse at the rate of 1800 per minute. As a result, only every other input signal was analyzed by the Enhancetron. The timing system was connected to the same power line as

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[1]The theory of operation of the signal averaging digital computer (Nuclear Data Model ND-800 Enhancetron-1024) used in this research is presented in the Appendix.

the synchronous motor so that even if a variation in the line frequency occurred, the relationship between the cuboid orientation and the trigger pulse timing was always constant.

When the desired measurements on a track had been made, the memory of the Enhancetron was viewed on an oscilloscope as shown in Fig. 10 and plotted by an X-Y pen recorder.

The entire apparatus is shown in Fig. 11.

C. Procedure

Tracks to be measured were located and aligned parallel to the slit by viewing them through the microscope using a 10x objective. After the track was positioned, the 10x objective was removed and replaced by a 100x oil immersion objective. The image of the straight wire filament of the light source was focused in a 2.5 micron-wide band in the plane of the track, with the track positioned in the center of this band. While viewing the photomultiplier output signal on an oscilloscope, the mirror angle was adjusted, thereby slightly changing the position of the light band in the emulsion, until the two lower peaks of the signal were the same height, indicating uniform illumination on each side of the track. Critical focusing of the track was accomplished by turning the fine focusing control until the maxi-

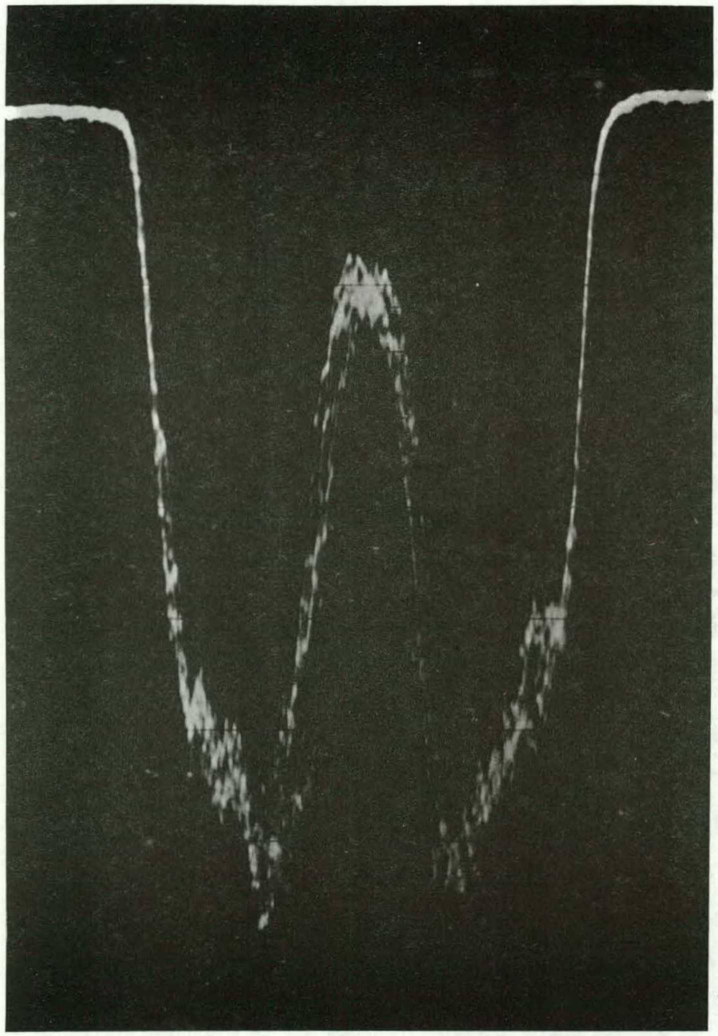

Fig. 9. Photomultiplier tube output signal

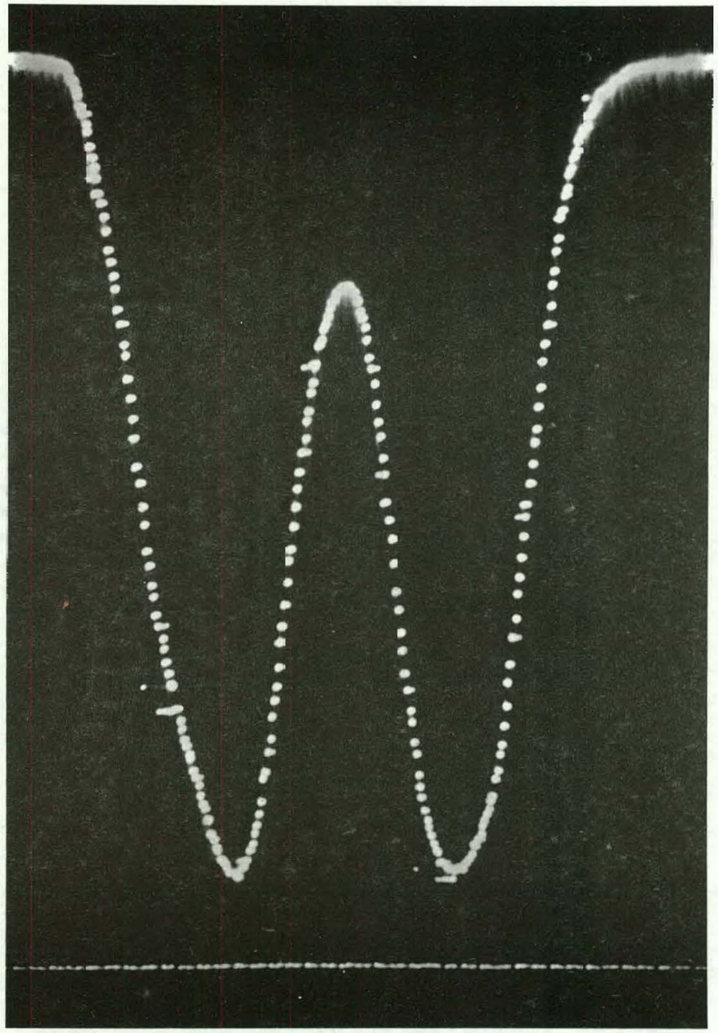

Fig. 10. Oscilloscope display of the averaged signal

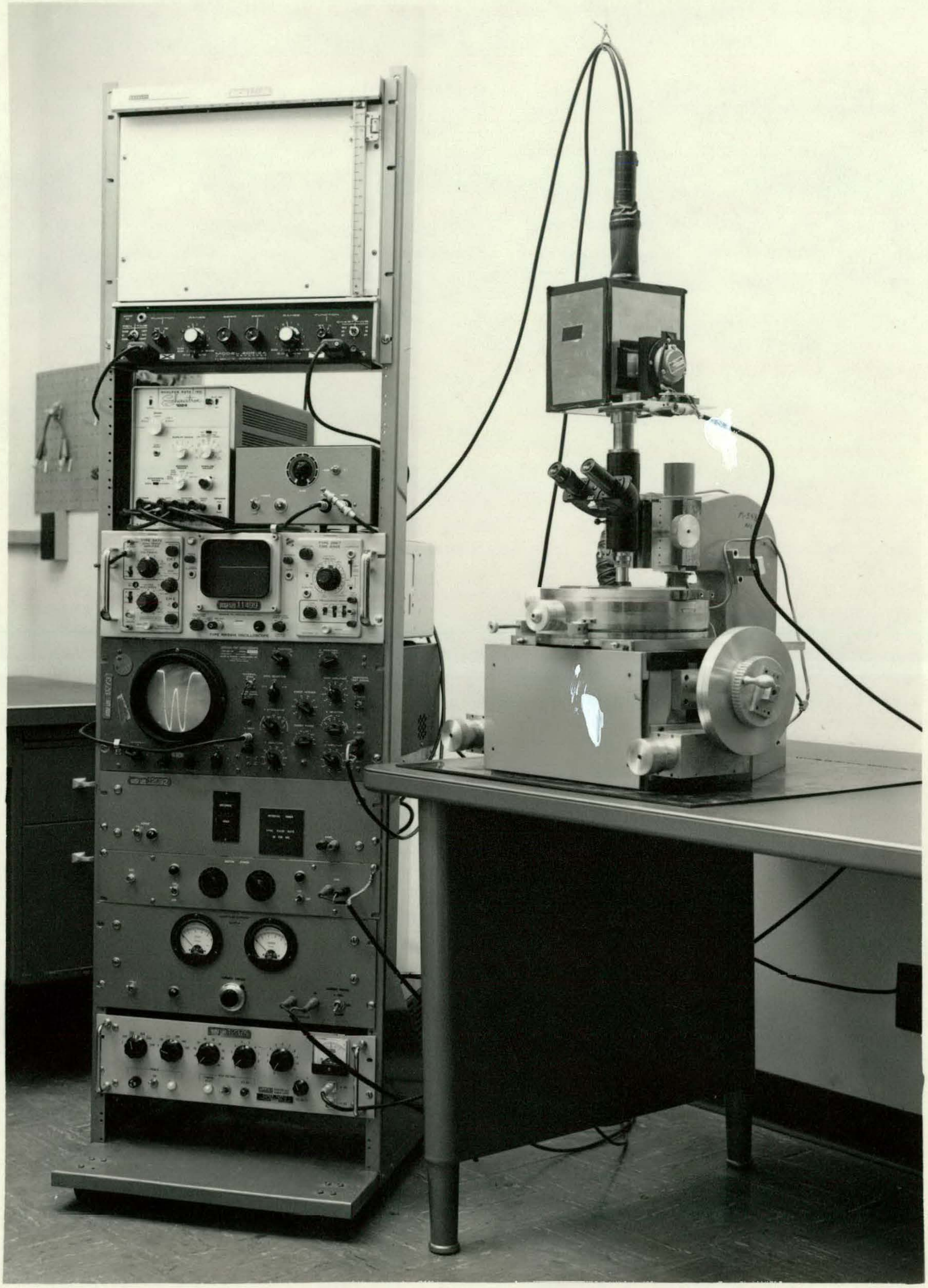

Fig. 11. View of the complete microdensitometer system

mum height of the center peak of the output signal was obtained.

Measurement was begun on each track at a distance of 10.0 microns before the particle came to rest in the emulsion, since the tracks of all particles are very similar near the end. Ten successive 5.0 micron segments were measured on each track. Each segment was measured for one minute, corresponding to 1800 sweeps being averaged and stored. Thus, for each track 50 microns were measured, and the resulting curve represented the average of 18,000 sweeps. The curve was plotted by an X-Y pen recorder and the value for the MTW of the track was calculated from this curve using Equation 3.

IV. EXPERIMENTAL RESULTS

A. Raw Data

In order to estimate the value of the microdensitometer, which was developed in connection with this research, in determining the charge of the particle producing an emulsion track, a group of 46 tracks was measured. These tracks were located in a stack of Ilford K5 glass-backed emulsion plates exposed to a 2.3 BeV/c beam of K^- mesons at the Alternating Gradient Synchrotron, Brookhaven National Laboratory. The emulsion plates were 6 inches by 4 inches and were 600 microns thick before development. The scanning of these plates was done by the Ames Laboratory Nuclear Emulsion Group under the direction of Dr. D. J. Zaffarano and Dr. Y. W. Kang. The 46 tracks which were measured had been identified through kinematical analysis by computer programs.

The measured tracks of particles of Z = 1 and Z = 2 were hyperfragments decaying through mesonic decay by the following modes:

$$_{\Lambda}H^3 \rightarrow \pi^- + He^3$$
$$\pi^- + H^1 + H^2$$
$$\pi^- + n + 2H^1$$
$$_{\Lambda}He^4 \rightarrow \pi^- + H^1 + He^3$$

$$_{\Lambda}H^4 \rightarrow \pi^- + He^4$$
$$\pi^- + n + He^3$$
$$\pi^- + H^1 + H^3$$
$$_{\Lambda}He^5 \rightarrow \pi^- + H^1 + He^4$$

The measured tracks of particles with Z = 3 were "hammer" tracks decaying through the following mode:

$$Li^8 \longrightarrow Be^8 + e^- + \bar{\nu}$$
$$\hookrightarrow He^4 + He^4$$

The number of tracks measured was relatively small because of the following restrictions placed on the tracks: (1) at least 60 microns long, (2) dig angle less than 45 degrees in the undeveloped emulsions, (3) portion to be measured did not cross a grid mark in emulsion, (4) did not suffer scattering. Fig. 12 shows the superposition of photoelectric track profile curves obtained for typical hydrogen, helium, and lithium tracks.

Each of the selected tracks was measured three times and an average MTW was computed for each track. The average MTW for each track is shown in Fig. 13 plotted as a function of the depth of the midpoint of the measured segment in the developed emulsion. The same MTW values are plotted in Fig. 14 as a function of the dip angle of the track in the undeveloped emulsion. In Fig. 15 the measured half-width of the profile curve of each track is plotted as a function of the dip angle of the track in the undeveloped emulsion.

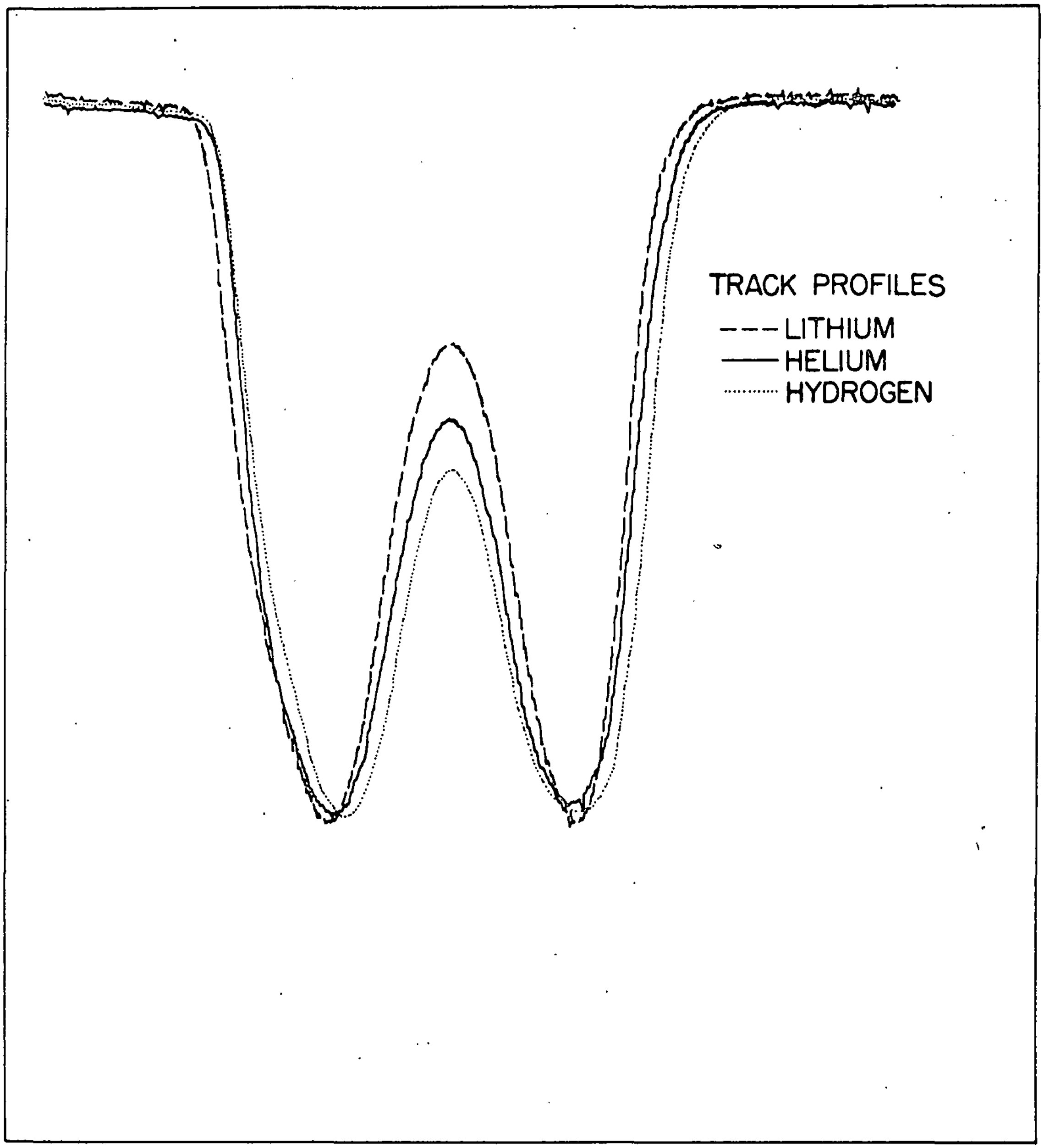

Fig. 12. Typical track profile curves

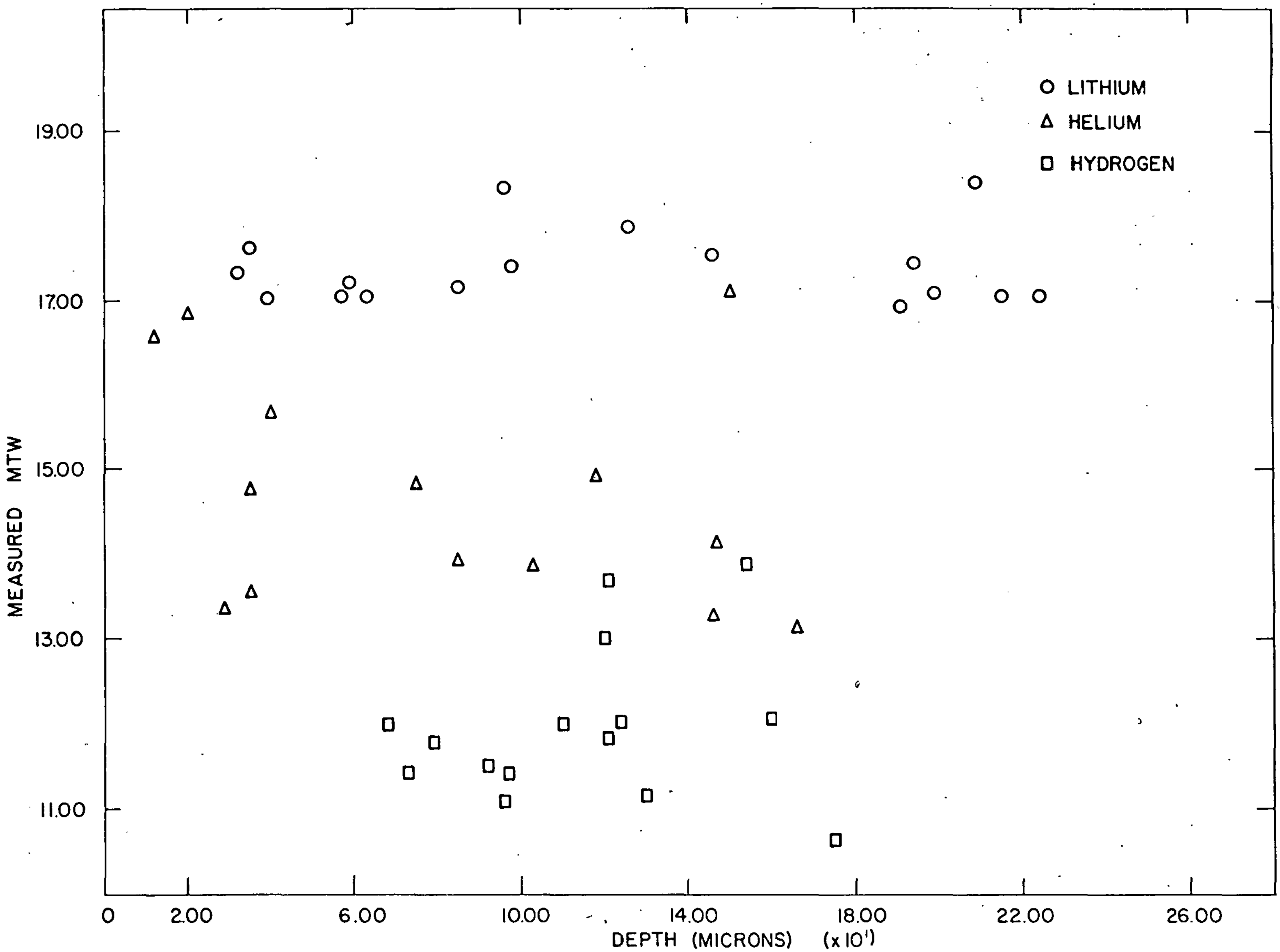

Fig. 13. Measured MTW values plotted as a function of the depth of the track in the developed emulsion; each point represents one track

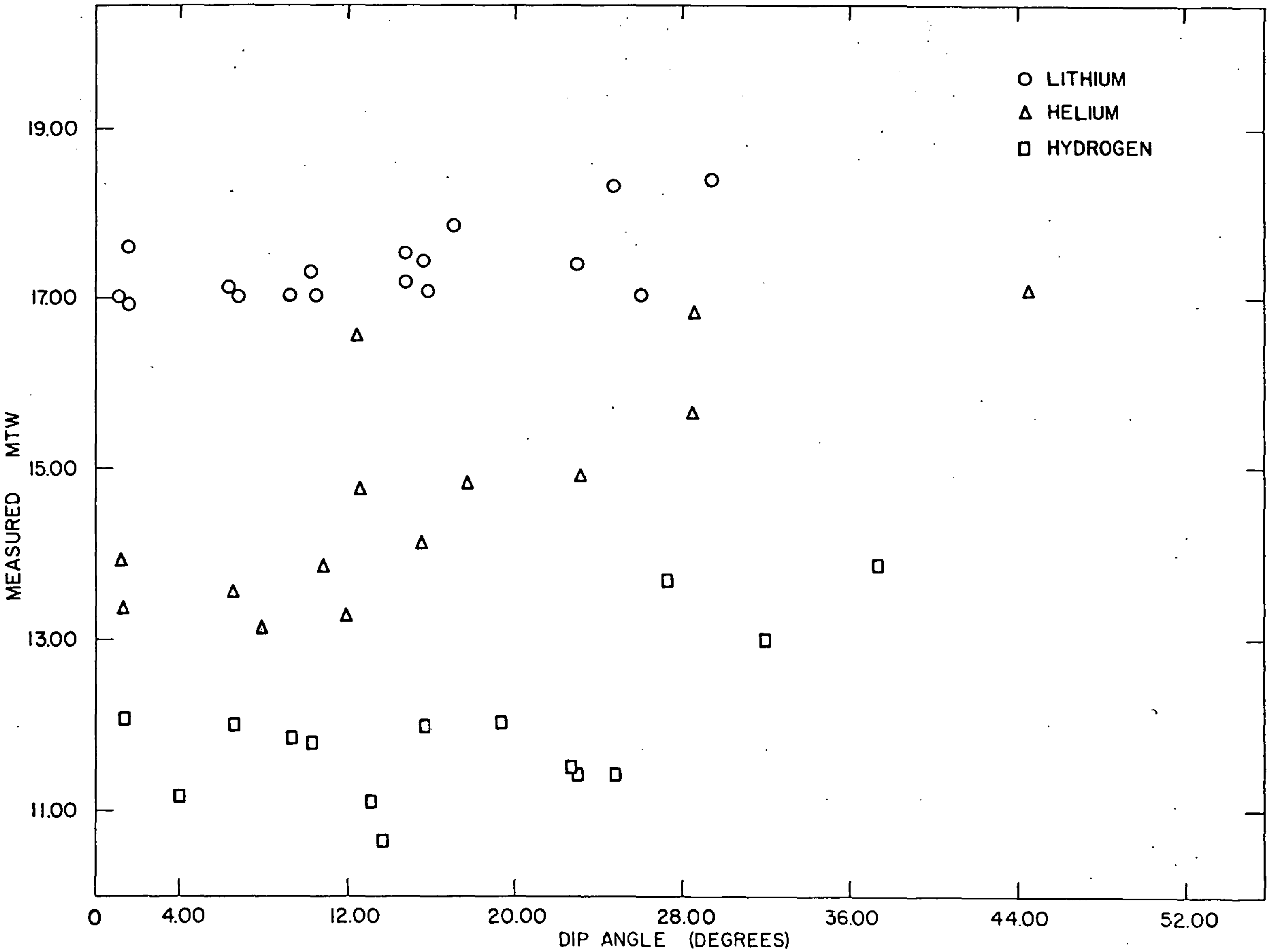

Fig. 14. Measured MTW values plotted as a function of dip angle in the undeveloped emulsion; each point represents one track

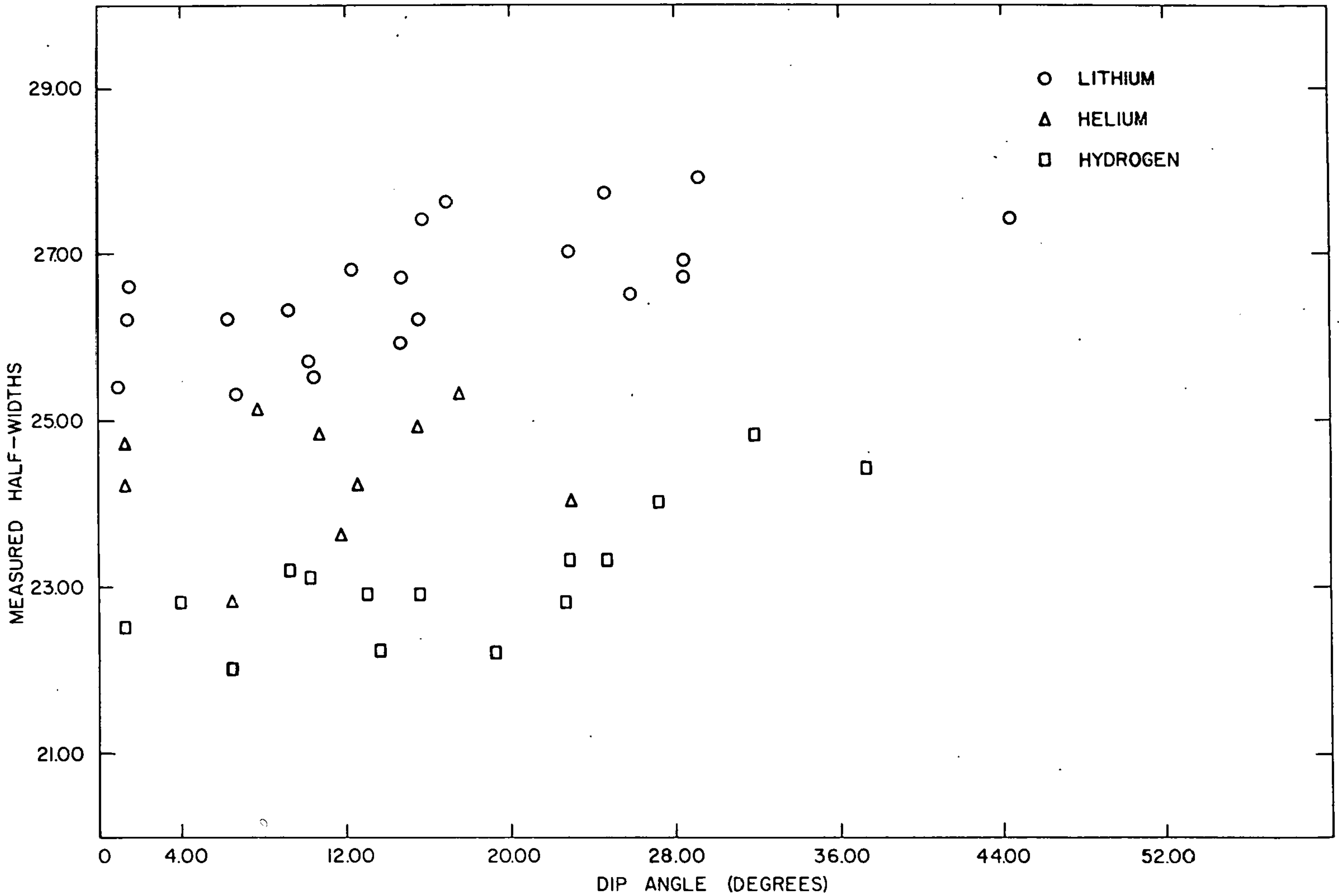

Fig. 15. Measured half-widths of track profile curves plotted as a function of dip angle in the undeveloped emulsion; each point represents one track

B. Depth Correction

The opacity of a track decreases as its depth from the surface of the emulsion increases due to the scattering of the light, which is projected upward through the bottom of the emulsion plate, into the image of the track. Increasing the distance between the track and the surface increases the number of molecules available to scatter the light into the track's image. In an effort to correct the measured MTW values for the depth of the tracks in the emulsion, the following measurement was made. A helium track about 5000 microns long was selected for measurement. This track, with dip angle of 6 degrees, had constant ionization from a depth of 131 microns in one emulsion plate to a depth of 173 microns in the emulsion plate directly above it[1]. Because of the small dip angle and uniform ionization of this track, MTW values of different portions of this track were considered to be dependent on only the depth of that portion in the emulsion. MTW values of different portions of this track are plotted in Fig. 16 as a function of the depth of that portion

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[1] Ideally a track traversing a single emulsion plate with low dip angle and constant ionization should be used, but such a track was not found in the group of emulsion plates examined in this research.

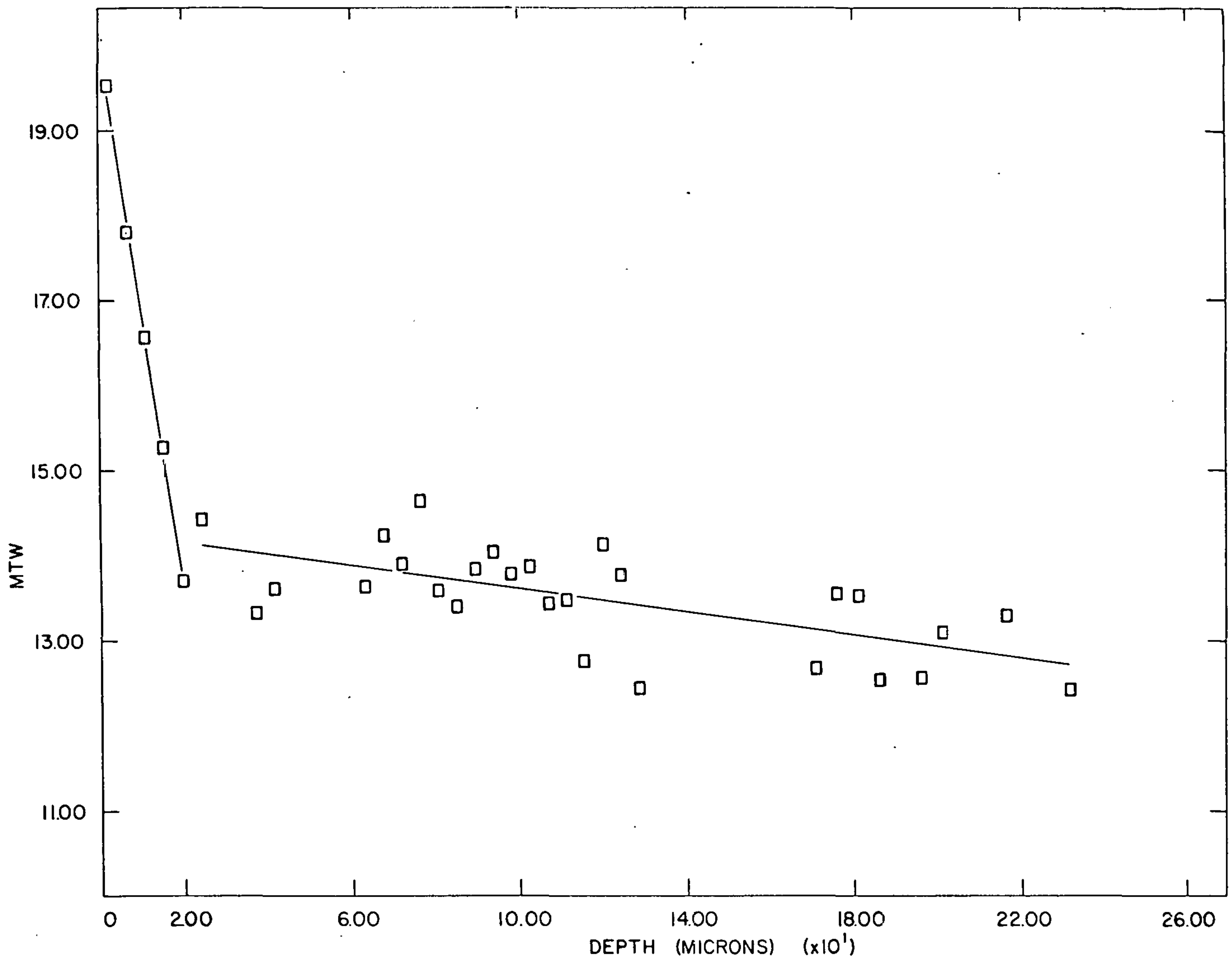

Fig. 16. Measured MTW values of portions of a helium track at different depths in the emulsion; each point represents the measurement of the length of track traversing a depth of 4.0 microns

in the emulsion. Two least-mean-square straight lines were drawn through these points as shown. If no depth dependence existed, these points should lie on a horizontal line. Correction factors for each depth were obtained from the straight lines of Fig. 16 by assigning the depth 100 microns a correction factor of 1.0. For a depth of x microns,

$$\text{correction factor} = \frac{(\text{MTW})_{100\ \text{microns}}}{(\text{MTW})_{x\ \text{microns}}} \quad . \tag{4}$$

C. Corrected Data

Using this method of depth correction, the measured MTW of each track was corrected. The corrected MTW values are plotted in Fig. 17 as a function of depth in the developed emulsion and in Fig. 18 as a function of dip angle in the undeveloped emulsion.

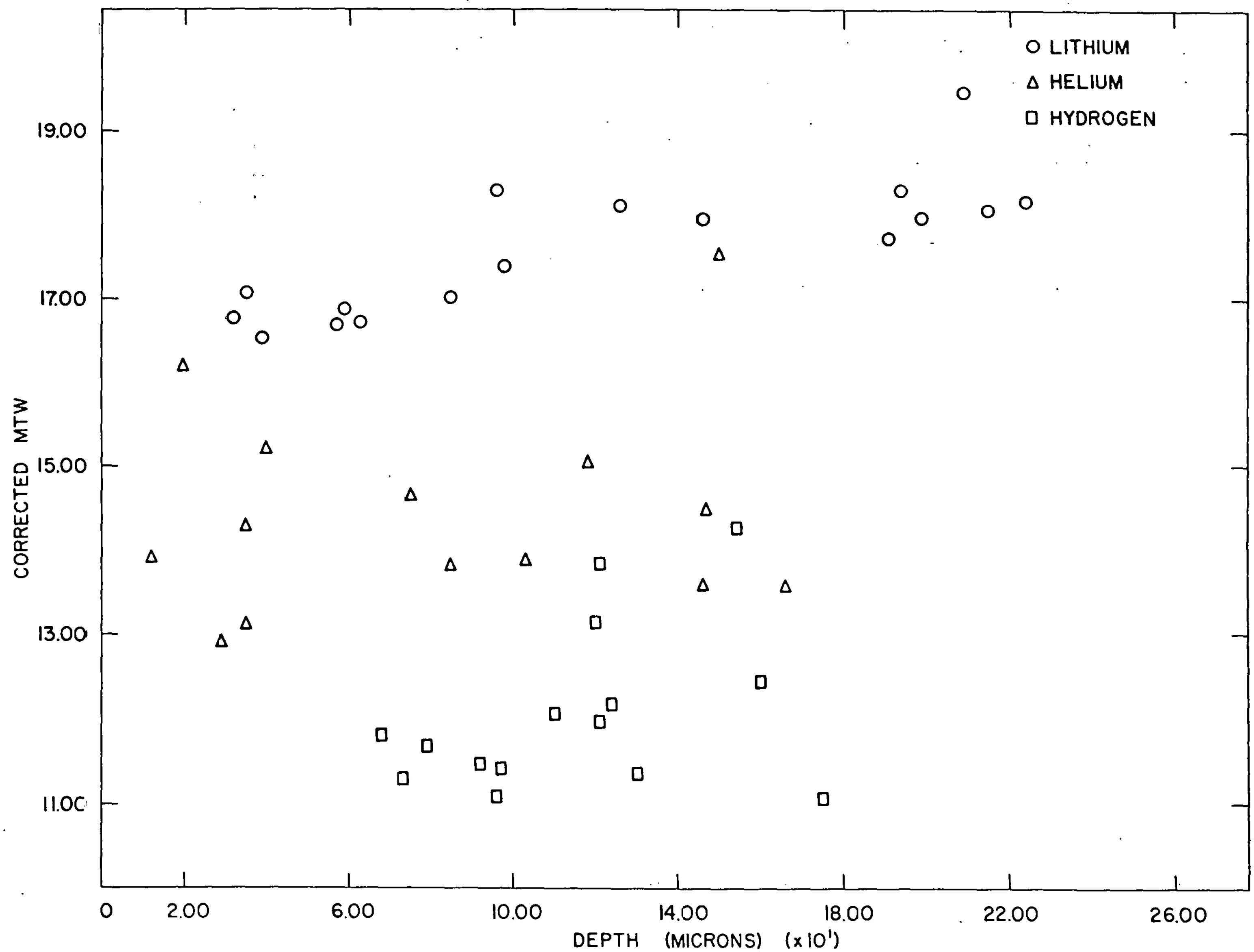

Fig. 17. Corrected MTW values plotted as a function of the depth of the track in the undeveloped emulsion; each point represents one track

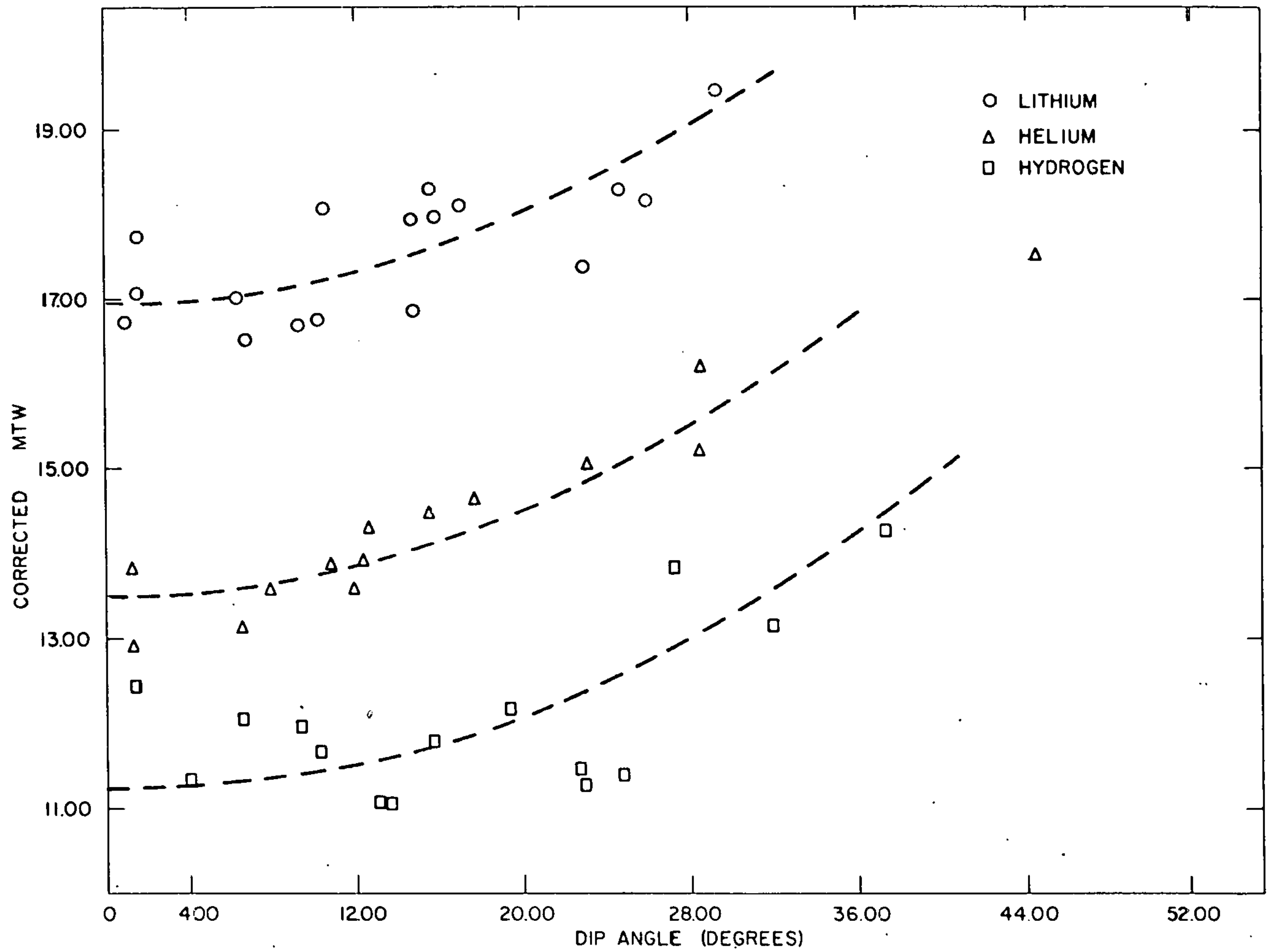

Fig. 18. Corrected MTW values plotted as a function of dip angle in the undeveloped emulsion; each point represents one track

V. DISCUSSION AND CONCLUSIONS

The measured MTW values were reasonably well separated into three groups, corresponding to Z = 1, 2, and 3, as shown in Fig. 14. Comparing Fig. 14 and 15, it is apparent that the measurements of MTW gave better separation of the charge groups than did measurements of the half-width of the profile curves of the tracks. These measurements did not indicate that half-widths are independent of depth as proposed by Ceccarelli and Zorn (13).

Fig. 17 shows that the opacity of tracks located within 20 microns of the surface of the emulsion plate varies greatly with depth, whereas the opacity drops only about 10% over the next 200 microns. Hence, except for tracks very near the surface, very little depth correction was necessary. This was mainly due to the fact that the band of light was kept very narrow. Although the depth correction used here was rather approximate, it improved the results so that there was complete separation in the charge groups as shown in Fig. 18. The dashed curves indicate an approximate expected dependence of MTW on the dip angle of the track. (An increase in MTW with increasing dip angle of tracks in each group is expected since the number of developed grains per unit projected length is increased.)

In order to get an estimate of the separation of the groups, the points of each group were fitted by least-mean-squares method to polynomials of order one through five. The second order polynomial was found to give the best fit. The best fit curves were found to be separated as follows: Between the Z = 1 and Z = 2 curves the separation was 3.5 root-mean-square deviations, except at angles less than 8 degrees; between the Z = 2 and Z = 3 curves the separation was at least 4.0 root-mean-square deviation over the whole range of angles.

The three measurements made on each track can be used to estimate the repeatability of the measuring system. The average deviation for each of the groups was the following: lithium, 2.0%; helium, 2.2%; hydrogen, 1.9%. It seems reasonable to ask if the largest MTW value of the three measurements of each track was not the most nearly correct value, since the track must have appeared optically more dense for this measurement. The maximum measured MTW value for each track is plotted in Fig. 19 as a function of the dip angle in the undeveloped emulsion. After depth correction, these measurements are shown in Fig. 20 plotted again as a

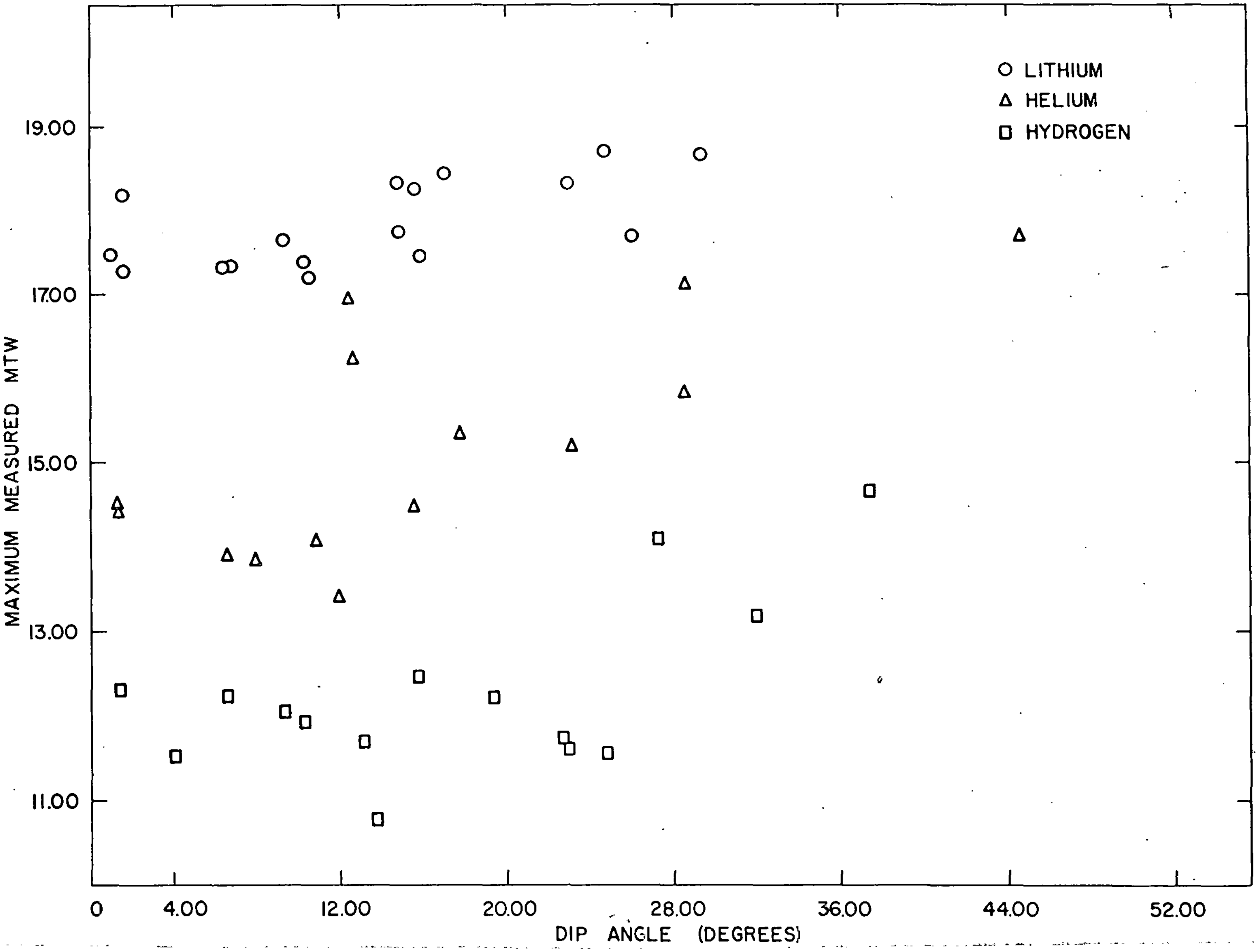

Fig. 19. Maximum measured MTW of each track plotted as a function of dip angle in the undeveloped emulsion; each point represents one track

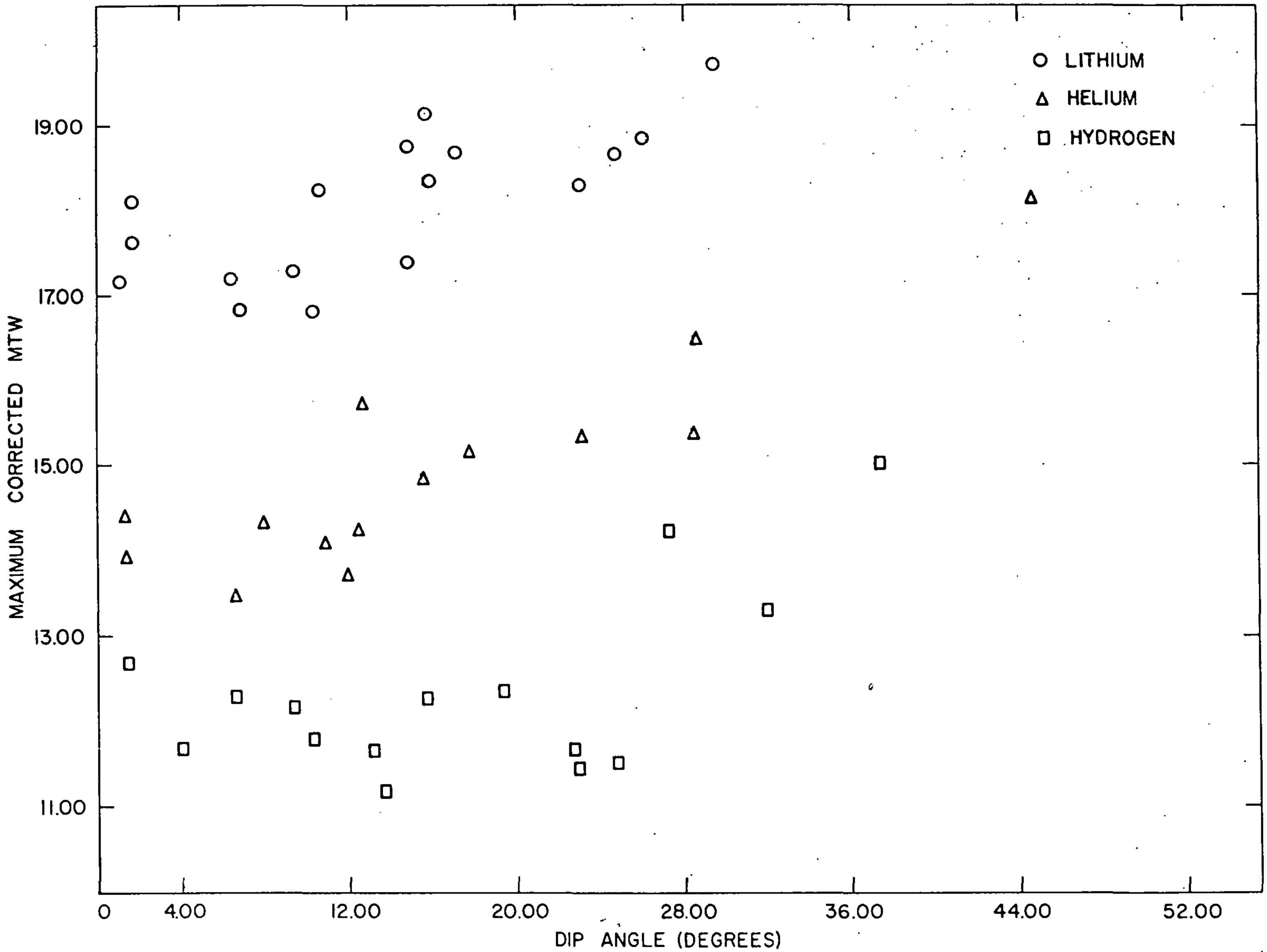

Fig. 20. Corrected maximum MTW of each track plotted as a function of dip angle in the undeveloped emulsion; each point represents one track

function of the dip angle in the undeveloped emulsion. Comparison of Figs. 20 and 18 shows that the results are not improved by using the maximum measured MTW for each track.

An effort has been made to identify possible sources of error in the measurements. To check the variation in the measuring system, a 1.5 micron-wide black line on a glass plate was measured every day over a 45-day period. The results are shown in Fig. 21. The standard deviation in in these measurements was 3.1%. (This line is about twice as wide as an average track; hence, the results may not be a perfect indication of the stability of the system.) No periodic variation in the measured MTW values is observed. It is believed that a large part of this error lies in the calculation of MTW from the profile graph. A digital readout unit for the Enhancetron is now available. Using this, the averaged profile curve from the Enhancetron could be obtained in digital form and the area under the curve could be calculated by a computer.

It has been concluded that no matter how elaborate the measuring system or depth correction method, sizable variations between MTW values for tracks of particles of like charge will always exist. This is due to local variations in

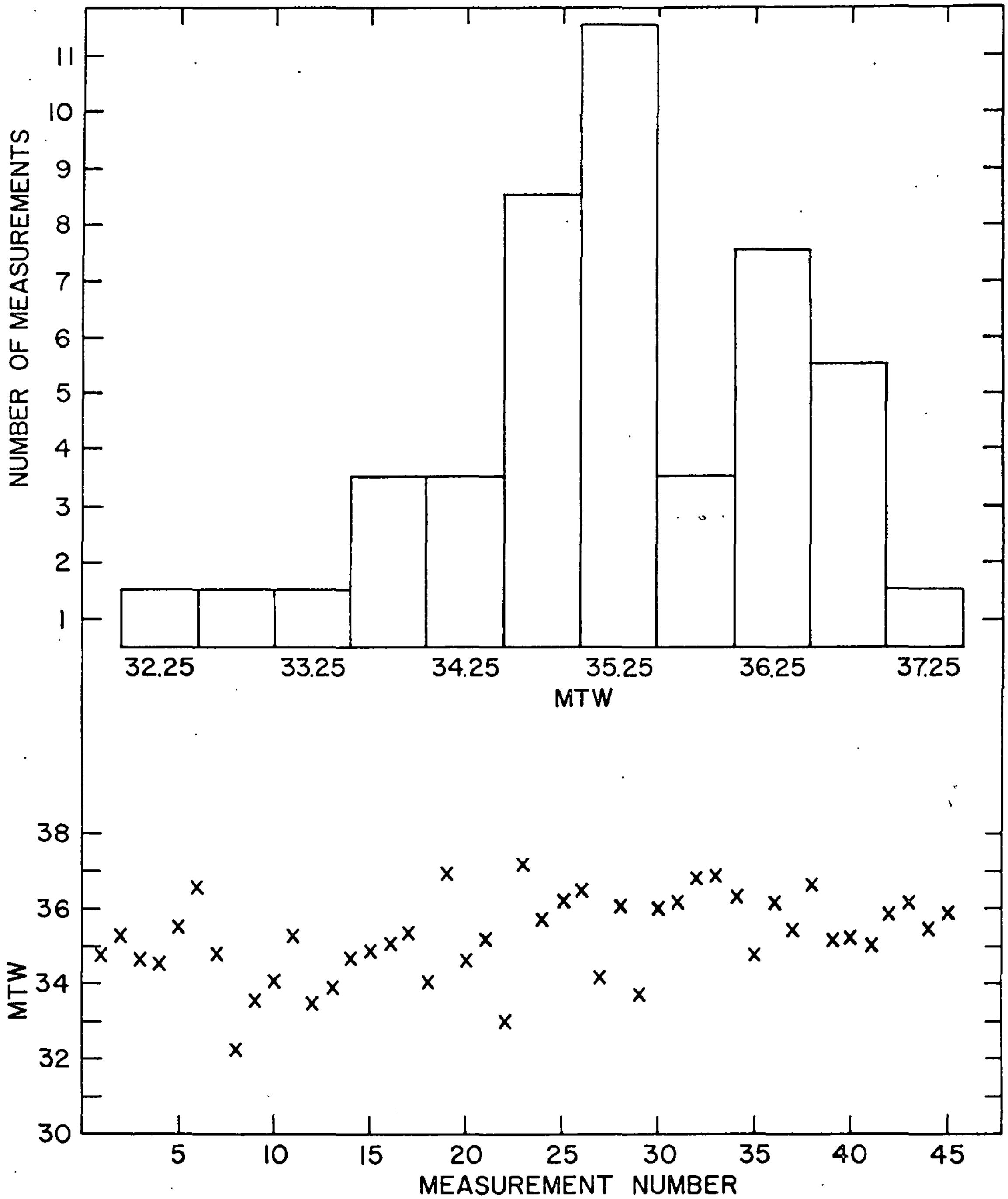

Fig. 21. Results of MTW measurements on a standard line

the emulsion development. In order to make the best estimate of charge of the particle producing a track, it is necessary to make MTW measurements on tracks in the same region of the emulsion as the track under consideration. The photoelectric mean track width method is a comparison process and, thus, requires calibration and depth correction measurements to be made on each different emulsion stack to be investigated.

The use of a signal averaging digital computer to store and average the profile curves has allowed more rapid and accurate measurements to be made than were previously possible. Using this system, it has been possible to measure the MTW of 50 microns of track length in less than 15 minutes and thereby separate tracks produced by particles of different charge.

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VIII. APPENDIX: THEORY OF OPERATION OF THE ND-800 DIGITAL AVERAGING SYSTEM

Using an electronic averaging technique, the Nuclear Data Model ND-800 Enhancetron-1024 extracts signals of interest from non-filterable noise. The Enhancetron utilizes 256 different reference voltage levels as a basis for comparisons to the input signal. The input signal may be divided into 512 or 1024 intervals; each interval corresponding to a channel in the memory of the Enhancetron. Noise adds or subtracts as the $\sqrt{N}$ at each point, while the signal component of interest adds or subtracts linearly by the factor N; N = number of sweeps. In the comparison process, the integrated value of the signal in each interval is compared with the reference voltage levels. Every reference voltage with an amplitude less than the integrated signal in a particular interval results in a count being added to the corresponding channel of the memory, and every reference voltage with a greater amplitude results in a count being subtracted from that channel in the memory.

Using the fastest storage rate of the Enhancetron, 0.016 seconds per 512 channels, one comparison is made per channel in each sweep. Since there are 256 randomly distributed reference levels, the comparison sequence, which dictates the order of selection of all 256 levels, is repeated two complete times per sweep at this storage rate. At the start of each sweep, the entire 256 reference level sequence is advanced by one so that a different reference level is used for each succeeding comparison in each channel until 256 sweeps have been made. Since for each digitizing operation the related memory cycle allows only one count to be added or subtracted from the memory contents of the appropriate channel, only a relatively few counts are necessary to define a given waveform. The Enhancetron allows analyzing both positive and negative signals since a sign bit is stored in the memory with each comparison.

A simple method of illustrating the digitizing process of the Enhancetron is shown in Table 1. Any number between -20 and +20, such as +13, is chosen and placed in Column A. This number is compared to all of the reference numbers in Column B. If the reference number is smaller than the number in Column A, a +1 is placed in Column C. If the reference number is larger than the number in Column A, a -1 is placed in Column C. The algebraic sum of these +1's and -1's is given in Column D. The sum of the numbers in

Column D is +13.

Table 1. Example of the digitizing process of the Enhancetron

A	B	C	D
+13	+20	-1	
	+18	-1	
	+16	-1	-4
	+14	-1	
	+12	+1	
	+10	+1	
	+ 8	+1	
	+ 6	+1	
	+ 4	+1	
	+ 2	+1	
	0	+1	+17
	- 2	+1	
	- 4	+1	
	- 6	+1	
	- 8	+1	
	-10	+1	
	-12	+1	
	-14	+1	
	-16	+1	
	-18	+1	
	-20	+1	