THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

THE USE OF PELLICLE STACKS TO STUDY HIGH ENERGY NUCLEAR INTERACTIONS

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PHILOSOPHY

BY

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Norman, Oklahoma

1956

THE USE OF PELLICLE STACKS TO STUDY

HIGH ENERGY NUCLEAR INTERACTIONS

APPROVED BY

DISSERTATION COMMITTEE

ACKNOWLEDGEMENTS

It is the author's pleasure to express his sincere thanks to Dr. Robert Adrian Howard for his guidance and encouragement in this dissertation.

It is also his pleasure to express his sincere thanks to Mr. J. S. Urban who aided in the processing of all the emulsions that were used in this research. He also would like to thank Mr. W. Z. Osborne for making the photomicrographs used in this work.

Finally, he would like to express his thanks to his wife who patiently stood by and gave inspiration for the several years it took to complete this work.

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THE USE OF PELLICLE STACKS TO STUDY HIGH ENERGY NUCLEAR INTERACTIONS

CHAPTER I

INTRODUCTION

For forty-five years photographic emulsions have been used to study the properties of charged particles. In particular they have been used extensively during the past ten years in the study of the cosmic rays at both high and low altitudes, and in the study of various nuclear reactions which occur when the emulsions are exposed to the radiation of the high energy accelerators. It has been found that it would be wise to increase the effective volume of the photographic emulsion available for the charged particles. One way to increase this volume would be to make stacks of pellicles and expose these to the high energy particles. The first portion of the present research was to establish a procedure for exposing and processing the pellicles at the University of Oklahoma. This procedure will be discussed in Chapter II along with the various advantages and disadvantages that one may expect in their use as compared with the use of the ordinary glass backed emulsions.

Ultimately one is interested in interpreting the various events that present themselves in the pellicle stacks. Many of the events reveal themselves in part by the number of delta rays that extend randomly from the tracks of the particles involved. A summary of the literature relative to the use of delta rays in particle analysis will be given in Chapter III of this dissertation.

During the scanning of a small stack of Ilford G-5 400-micron pellicles that had been exposed to the cosmic radiation[1] at an elevation of 93,000 feet, the author found an interesting event. This event will be discussed in detail in Chapter IV of this dissertation.

Subsequently, another stack[2] of Ilford G-5 400-micron pellicles was partially scanned by the author. Another interesting event was found which, although it was not unusual, had some characteristics which made it worthy of an analysis. This event will be discussed in Chapter V of this dissertation.

Finally, in Chapter VI, there will be a summary given of this dissertation.

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[1]Flown by the courtesy of the ONR project "Skyhook" at San Angelo, Texas (31° 27′ North Geomagnetic Latitude) on January 18, 1955.

[2]Flown by the courtesy of Major David G. Simons of Holloman Airforce Base, at an altitude of 130,000 feet at about 56° North Geomagnetic Latitude.

CHAPTER II

THE PROCESSING OF STRIPPED EMULSIONS

Pellicles can be processed either before or after they have been mounted on rigid glass supports. The advantage of processing them before they have been supported is that the chemical solutions can penetrate the emulsion from both faces, thus greatly reducing the time-consuming processing procedures. The disadvantage encountered in the processing of the pellicles before they are supported is that they suffer a permanent lateral swelling that so distorts the tracks that multiple scattering measurements, as now taken, are meaningless. This disadvantage can be overcome if the pellicles are properly placed on rigid supports before processing. One must be careful in the mounting procedure, however, so as not to introduce harmful blistering[1] in later stages of the processing.

The nuclear emulsion laboratory of the University of Oklahoma has so far adopted the procedure of mounting the pellicles before processing. This procedure and the processing of the pellicles will now be discussed.

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[1]"Blisters" in the emulsion are small regions in the emulsion ranging from about a millimeter, up to several millimeters in diameter that arise wherever the emulsion has come loose from the support and swelled to the extent that it gives the appearance of a blister.

First, it is necessary to have the pellicle stack exposed to the type of radiation that one wishes to study. This is done according to the procedure recommended by Fitzpatrick[1]. As soon as the pellicle stack is returned, one must measure the thickness of each pellicle[2]. Then, the set of specially processed 1 in. by 3 in. plates that were purchased from Ilford, Ltd., must be placed in a container[3] of distilled water with wetting agent[4] and allowed to soak for at least twenty minutes. For the best results it was found that this detergent solution should be kept at a temperature of 26° C. These specially treated plates are characterized by the fact that on either face there is a three micron thick coating of gelatin. The soaking time is necessary to give the distilled water a chance to completely permeate this thin gelatin layer. The specially treated glass plates are now ready for the pellicles to be mounted. To mount the pellicles one of the special plates is placed in the recess in the plastic holder shown in Fig. 1. This recess is 1 in. by 3 in. in area and about 200 microns deeper than

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[1]Philip M. Fitzpatrick, "The Interaction of Extremely Energetic Cosmic Ray Particles with Matter" (Unpublished Ph.D. dissertation, Dept. of Physics, University of Oklahoma, 1955).

[2]This will enable one to determine the shrinkage factor which is the ratio of the thickness before processing to the thickness after processing.

[3]A suitable container is the glass tank that heretofore had been used as a developing tank.

[4]So far at this laboratory aerosol O. T. has been used as recommended by Stiller, although the commercial detergents "Glim" or "Joy" would perhaps serve the same purpose. B. Stiller, M. M. Shapiro and F. W. O'Dell, Rev. of Sci. Instr. <u>25</u>, 340 (1954).

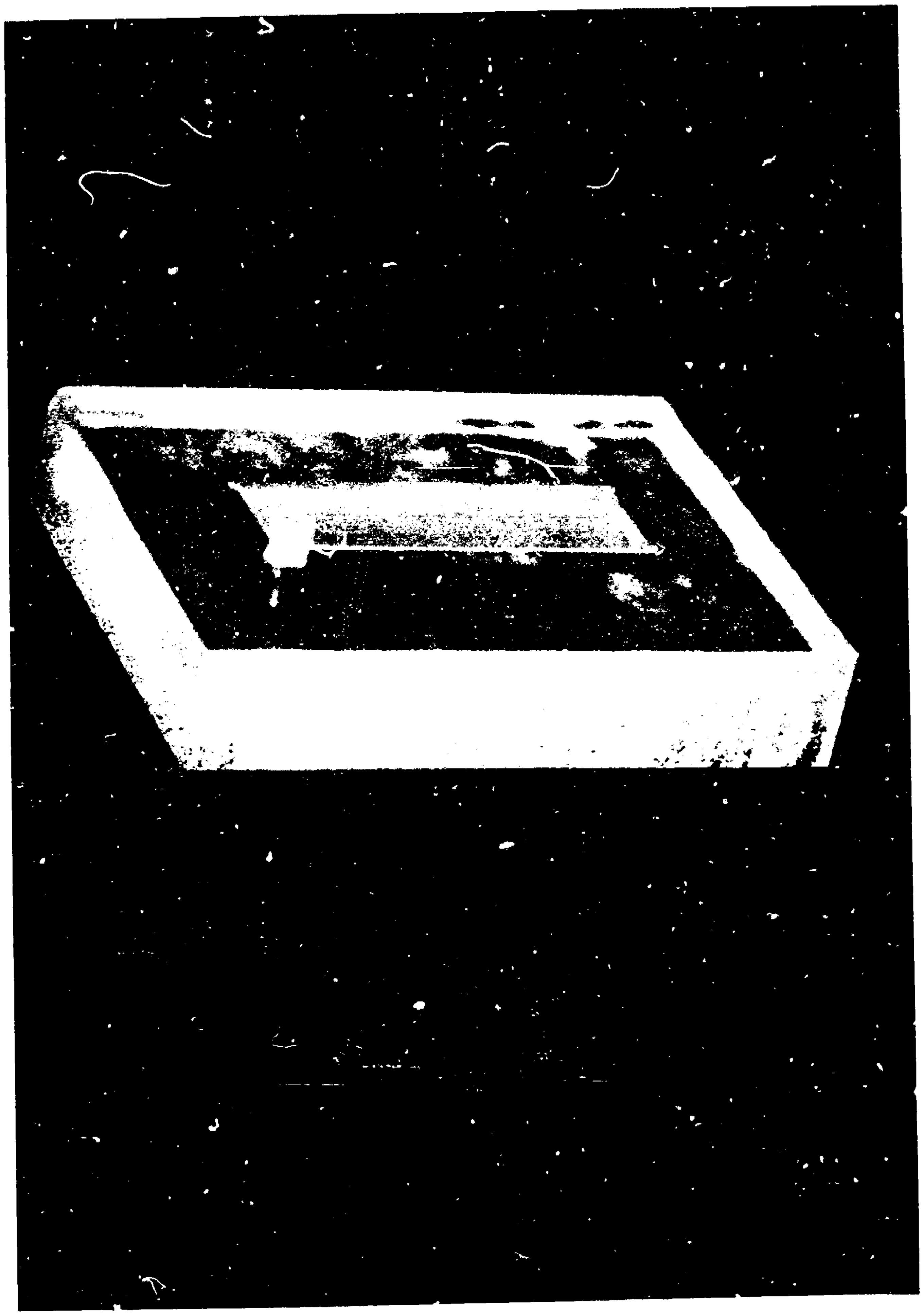

Fig. 1. -- The plastic piece with recess to guide the pellicles onto the treated glass plates.

the thickness of the special plates. Next, the glossy side of the pellicle to be mounted is swabbed gently with cotton that has been dipped into the distilled water-wetting agent mixture until the face appears completely wet as viewed under a safelight[1]. With the recess above the plate as a guide, this glossy side is then aligned on the treated plate. The step of placing the glass plate in the recess, swabbing the glossy side of the pellicle and aligning the pellicle on the treated plate must be done as rapidly as possible so as not to allow any spot on either the plate or the pellicle face to become partially dry. If any dry spots should occur, then the pellicle would not adhere to the plate at these places. Next, a piece of thin polyethylene sheet is placed over the top face of the pellicle. This cover must be such that no wrinkles appear therein and it thus acts as a protective cover during the next step, which consists of gently rolling the pellicle with a photographic print roller from its central portion toward the edges. The polyethylene sheet used in this manner prevents harmful scratches on the pellicle surface during this step. Next, one should place a smooth weight of about ten pounds on the polyethylene cover and allow it to remain undisturbed for ten minutes. The weight is then removed and the polyethylene cover is slowly peeled off at a small angle of contact[2] with the pellicle face. Then the plate with the mounted pellicle is removed from the recess and

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[1]This is an ordinary red photographic safelight.

[2]This precaution is necessary because during the rolling procedure and the ten minute adhesion period the polyethylene and pellicle surface adhere slightly and one can rip the pellicle from the plate if not extremely careful.

placed on the table in the microscope room to dry for nine hours. This drying time is recommended by Stiller[1]. In fact, the entire mounting procedure has heretofore been carried out in the microscope room because it is felt that even in this stage of the processing one may be able to prevent some harmful distortions if the temperature and humidity conditions which the pellicle experiences are controlled.

During the mounting procedure one must be careful not to destroy the alignment maintained in the pellicle stack during the exposure. This is done by removing the pellicle from the stack and being careful to remember to maintain this orientation while placing it on the treated plates. Once the plates are removed from the recess a code mark must be placed in a convenient place on the plate to designate the proper orientation.

One might first believe that the pellicles could be wet by completely immersing them in the wetting solution for a very short time. This is not recommended according to Stiller[2], however, since he has found that this greatly increases the number of harmful blisters in the emulsion. When the recommended procedure was followed, blistering was encountered in this laboratory but not to any great extent.

After the pellicles have been mounted they are then processed just as ordinary emulsions of the same thickness. Since the pellicles used for this research were of the same dimensions as those used by Fitzpatrick[3], the processing procedure used by him was followed in this research

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[1]Stiller, op. cit. [2]Stiller, op. cit.

[3]Fitzpatrick, op. cit.

as far as the solutions used are concerned. However, it is felt that some improvement has been made in that the number of hours one must actually monitor the processing steps has been greatly reduced due to a series of experiments carried out in this laboratory[1]. Also, it is believed that the stainless steel processing tank of which an isometric view is shown in Fig. 2, represents a great improvement over the one used by Fitzpatrick[2].

In Fig. 3 there is a photograph of the trays used to hold the emulsions during the wet processing stages. The trays are each equipped with three pairs of beveled dovetail ribs so that they will hold two rows of ten 1 in. by 3 in. emulsions and one row of eight 1 in. by 3 in. emulsions. There are now four of these trays which can be mounted or removed from the central vertical support. The trays are held apart on the support by one inch spacers. With this set-up the laboratory can handle one hundred sixteen of the 1 in. by 3 in. plates simultaneously. This support has been constructed so that six more trays can be added in the future if it is desirable to handle a larger number of nuclear plates. From the nature of the trays it is clear that if one of the cross sectional dimensions of the plate is held to three inches it is possible to develop various size plates without making any major adjustments in the tank and trays. To insure that the plates remain level during the wet

[1]These experiments were carried out by Mr. Horace E. Hoffman at this laboratory during the summer of 1954. These experiments were aimed at finding the proper refrigerator setting and controls one could employ so as to dispense with using crushed ice. The procedure recommended here can be found in H. E. Hoffman Research Notebook I, 2, 1954.

[2]Fitzpatrick, *op. cit.*

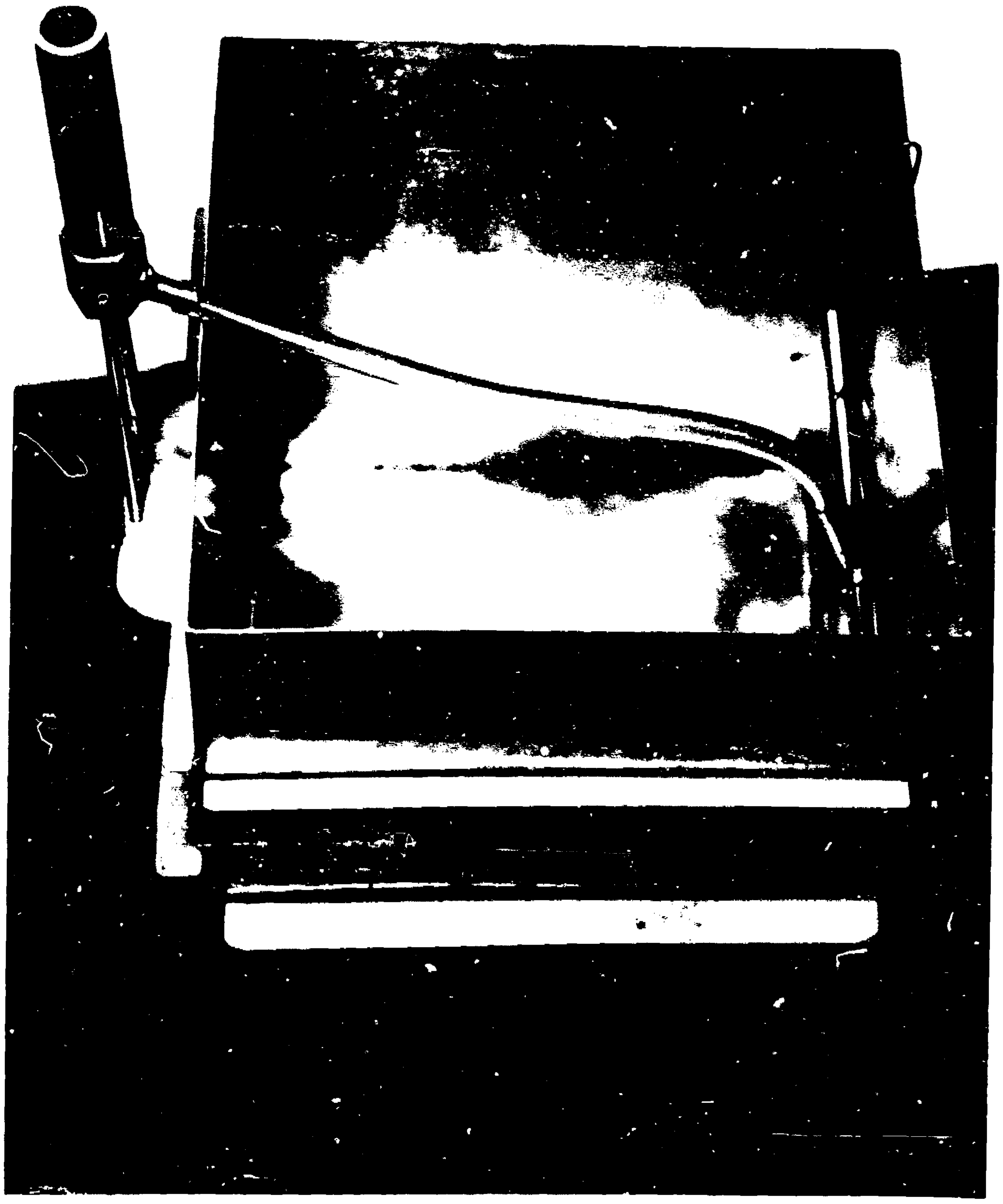

Fig. 2. -- The Stainless Steel Developing Tank

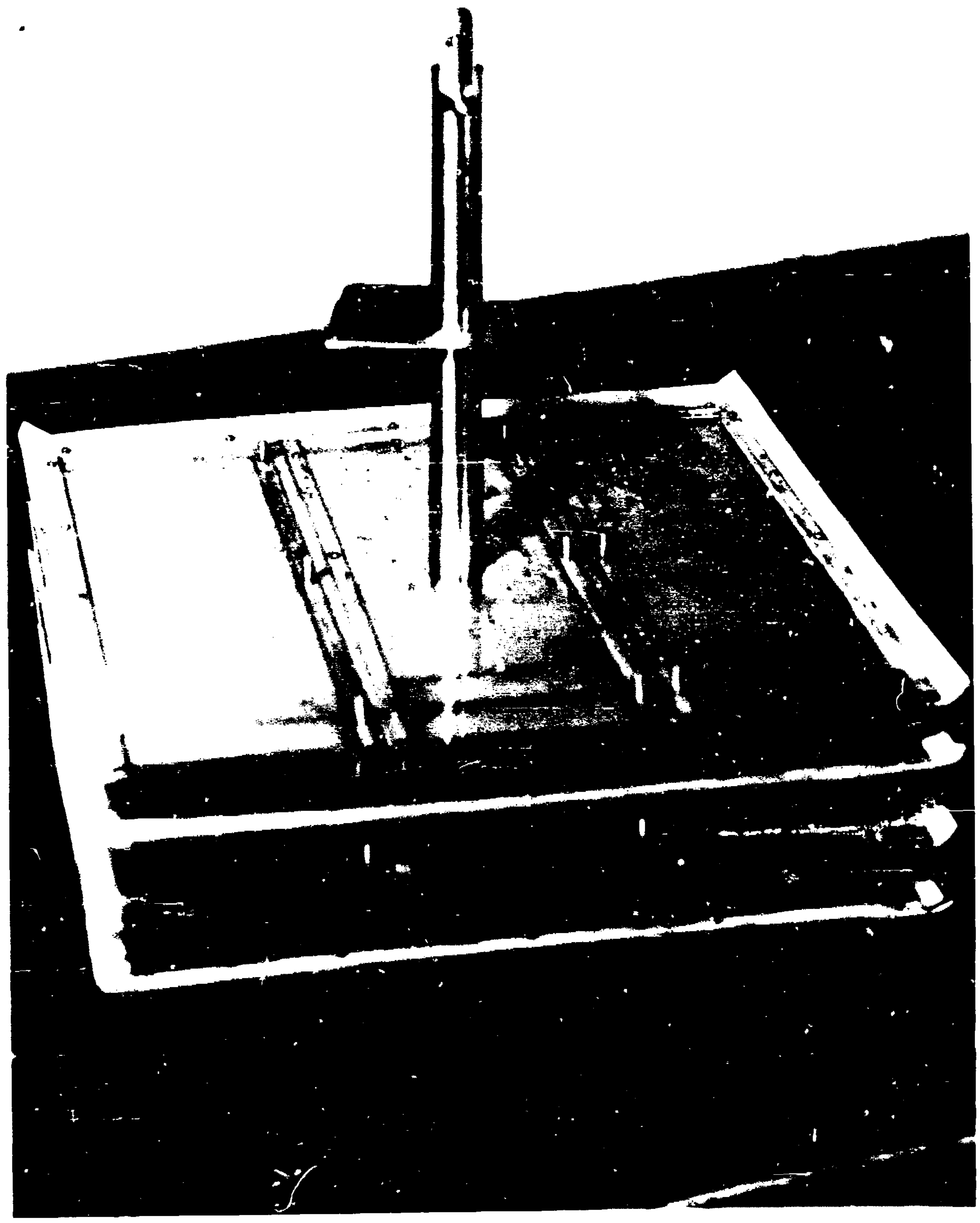

Fig. 3. -- The trays with levelness indicator (spirit levels) on the shaft.

processing stages the support is equipped with a "level" consisting of a leveling bubbles on two adjacent sides of a small rectangular plate. The leveling is done by lifting and pushing on the handle at the top of the central vertical support. When each bubble is centered the trays are level.

In order to make the fixing and clearing stages as nearly automatic as possible[1], an "impact pump" was obtained which is shown in Fig. 4. This pump circulates the solution in the tank and thus acts to agitate the solution. Because of corrosion, this pump cannot be connected directly to the reservoir of the liquid being used and thus continually remove the contaminated liquid from the tank and replace it by pure solution from the reservoir. Accordingly, plans have been made to equip the apparatus with a pump suitable for corrosive liquids.

Finally, Fig. 5 shows the entire assembly as it is used in the wet processing stages. So far one batch of forty-eight of the 1 in. by 3 in. by 400 micron emulsions has been processed with this arrangement. The results were satisfactory but not as good as were expected in that about ten of the plates did not fix properly. It is believed that this failure was due to the fact that the trays were arranged in the tank in such a manner that the liquids did not circulate properly. This can be prevented in the future by properly arranging the teflon baffles that are fitted on three edges of the trays for the purpose of setting up the proper fluid flow. The edge without the teflon baffle should be at the

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[1]This was suggested by H. E. Hoffman during his experiments in the summer of 1954.

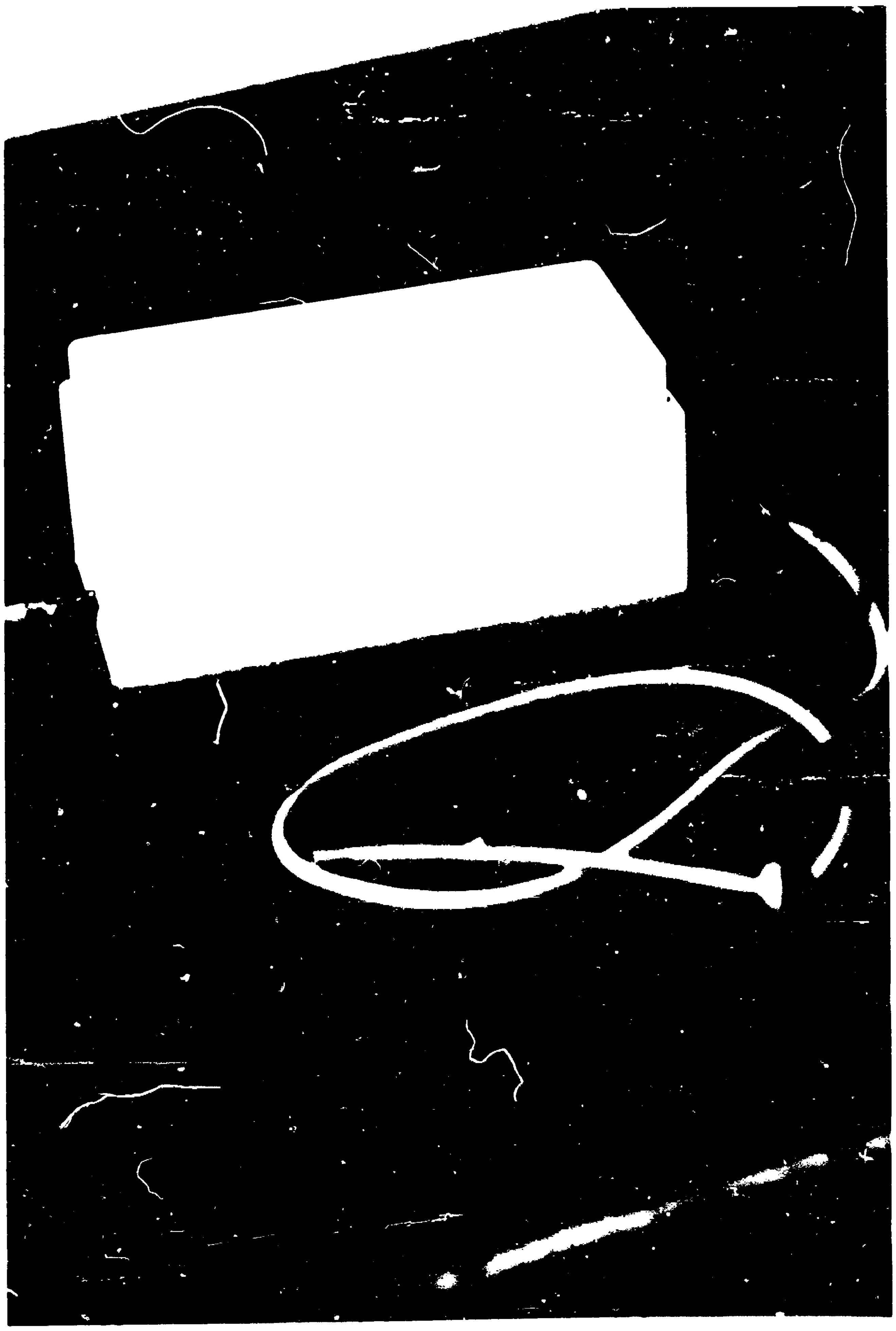

Fig. 4. -- The "impact pump" used to circulate the fixing and washing solutions.

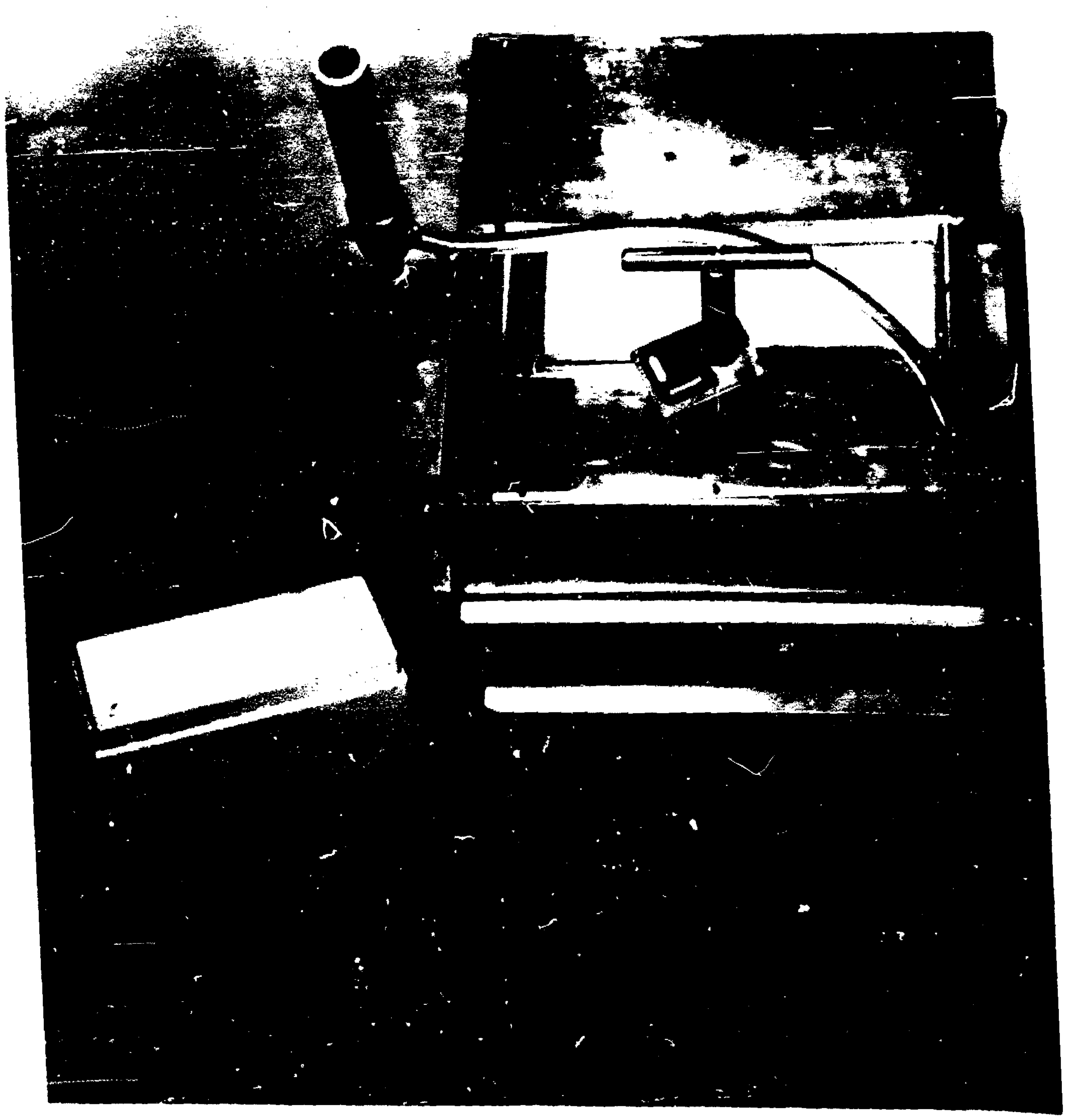

Fig. 5. -- The entire assembly for developing nuclear emulsions.

back (edge opposite the point of entry of the fluid through the hose). The fluid will then flow from the hose to the front edge of the top tray and then to the back edge of this tray; then down to the second tray and back to the front edge, and so forth until the fluid has made a complete circuit. It was noticed that these trays were oriented 180 degrees from this position for the first fifteen hours of the fixing process; this made it impossible to maintain a proper flow for this period.

CHAPTER III

DELTA RAYS

Introduction

In many of the high energy events with which one deals, it is quite clear that it is safe to make the assumption that the charge number Z of a particle is known to be a certain value. With this assumption regarding the charge, and with the use of the range energy relation[1] $R = \frac{hM_o^{1-\nu}E^{\nu}}{Z^2}$ along with either constant cell-length scattering or constant sagitta scattering, one can find the value of the rest mass M_o, the residual range R, and the energy E of the particle, provided the values of the empirical constants h and ν have been determined.[2] On the other hand, there are many cases for which one cannot safely assume a value for the charge number Z in which case it is necessary to be able to determine this from some other information in the track. This other information is usually obtained by counting the number of delta rays along the track that meet certain specifications. The manner in which this information is obtained and used will now be discussed.

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[1]Fitzpatrick, Loc. cit.

[2]In the cosmic ray laboratory at the University of Oklahoma, the numerical values of 2860 and 1.76, respectively, have been used for these two constants.

Methods Used

The basis for using the information obtained from delta rays is the Rutherford equation[1], which is

$$dN_{\delta} = \frac{2M_ec^2Z^2}{\beta^2} C \frac{dE'}{E'^2} \qquad (3\text{-}1)$$

where,

M_e is the rest mass of the electron;

c is the velocity of light;

Z is the charge number of the particle under consideration;

βc is the velocity of the particle under consideration;

C is a constant of the emulsion equal to $\frac{N \mathcal{Z} \pi r_e^2}{A}$, which is the electron cross-section per gm/cm^2 of the stopping material, since N is Avogadro's number, $\mathcal{Z}$ the average atomic number of the emulsion, r_e the radius of an electron and A the average atomic weight of the emulsion;

dN_{δ} is the theoretical number of delta rays that will be ejected per unit path having an energy between E' and $E' + dE'$.

In the first publication[2] in which use of this information was made, the number of delta rays was counted along the track so that the total number of delta rays per unit track length having an energy be-

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[1]Bruno Rossi, High Energy Particles, McGraw Hill, New York, p. 137 (1952).

[2]P. Freier, F. Lofgren, E. Ney, F. Oppenheimer, Phys. Rev. 74, 1818 (1948).

ween E'_{min} and E'_{max} could be compared to the number predicted theoretically by integration of the Rutherford equation between the same two energies as limits. The lower limit E'_{min} for the integral of the Rutherford equation is invariably fixed by a "counting criterion"[1]. These observers demanded that the delta ray track have a perpendicular projection from the core of track of the incident particle of at least 1.5 microns. This counting criterion is referred to as the "range criterion" and, since these observers used the Ilford C-2 type emulsions, corresponded to an energy E'_{min} of 10 Kev. E'_{min} is believed to be about the same for this criterion regardless of the type of emulsion used since the stopping powers of all commonly used emulsions are approximately the same. The upper limit E'_{max} is taken to be the smaller of the following two energies:

1. The maximum energy that can be transferred to an electron, which is initially at rest, by the impinging particle.

2. The maximum energy that an electron can have and still be detected by the emulsions being used. This corresponds to electrons of about 70 Kev, for the Ilford C-2 emulsions whereas it would be infinite for the emulsions that detect minimum ionizing particles such as the Ilford G-5 emulsions. It is clear that when using Ilford G-5 emulsions, the first of these always sets the upper limit, whereas the second sets the upper limit for the Ilford C-2 and emulsions

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[1]A "counting criterion" is a criterion adopted for deciding which tracks are to be counted as delta rays. This is necessary to enable one to reduce to a minimum the number of background tracks counted as delta rays.

of like sensitivity. Integrating equation (3-1) between the limits of $E'_{min} = E_1'$ and $E'_{max} = E'_m$ one obtains

$$N_\delta = \int_{E_1'}^{E_m'} \frac{K'Z^2}{\beta^2} \frac{dE'}{E'^2} = \frac{K'Z^2}{\beta^2}\left(\frac{1}{E_1'} - \frac{1}{E_m'}\right) \tag{3-2}$$

where $K' = 2M_ec^2C$ and where it should be kept in mind that β remains essentially constant over the unit of path length under consideration. For relativistic particles $E'_m = 2M_ec^2$ in which case one may write

$$N_\delta = \frac{KZ^2}{\beta^2} \tag{3-3}$$

where $K = K'\left(\frac{1}{E_1} - \frac{1}{E'_m}\right)$.

The expression given by equation (3-3) gives the number of delta rays, per unit length of track with energies E' such that the condition $E_1' \leq E' \leq E'_m$ is satisfied. When a count is made on the delta rays per unit length of the path, however, under the criterion being used, one will always find a number N_δ which is less than the predicted number. This is due to the fact that not all the delta rays having these energies will have a projected path of 1.5 microns from the core of the track. Some delta rays will be projected parallel to the track direction, some will be ejected parallel to the line of vision, whereas others will curl around the track itself several times. Such delta rays are missed by virtue of the counting criterion. This must be compensated for before the delta ray count can be compared satisfactorily with the number of delta rays predicted by the theoretical expression. This is done by calibrating the emulsions for delta rays. Freier[1] and her co-workers calibrated the emulsions by finding N_δ for tracks of various known particles that stopped in the emulsion. This enables one to find the value of K in equation (3-3). With this value of K determined, one is then ready to use the delta ray density N_δ as one of the parameters in the identification of a particle.

For particle identification then, one begins by calibrating the emulsions to determine the K to put in equation (3-3). However, there are two unknowns Z and β in this equation, so one must have at least one other equation involving the same two unknowns. The second equation can be obtained by considering two possible cases for a given particle. First, there is the case in which the particle comes to rest in the emulsion and secondly, there is the case in which the particle escapes from the emulsion before coming to rest. In the first case one can use the range energy equation as found by Fitzpatrick[2], which is

$$R = \frac{hM_o^{1-\nu}E^{\nu}}{Z^2} \qquad (3\text{-}4)$$

where $E = \frac{1}{2}M_o\beta^2c^2$. This case will now be discussed essentially in the manner it was used by Freier[3], after which the procedure that was adopted by the same investigators to handle the second case, will be discussed.

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[1] Loc. cit.

[2] Fitzpatrick, op. cit.

[3] Freier, op. cit.

For the first case, there are several ways that one may proceed.

First, one can assume a value for β and substitute this value into equation (3-3). This equation is then solved for Z. Then it is assumed that $M_o \cong 2Z$, where M_o is mass of the particle in a.m.u., and this value of M_o is substituted into equation (3-4) along with the measured value of R. Equation (3-4) is then solved for β and if this computed value of β agrees with the assumed value of β, then Z is considered determined for the particle. If this value of β does not agree with the assumed value, then one begins the same procedure with a different value of β and this is continued until the assumed value and the computed value agree with each other to within statistical fluctuations.

A variation of this procedure, sometimes used by these investigators, was to assume a value for β and solve equation (3-3) for Z as before. From curves of E versus R for various values of Z of known particles, one could find the value of E for the value of the residual range R. Then, since

$$E = \tfrac{1}{2}M_o\beta^2c^2 \qquad (3\text{-}5)$$

one could solve this for β, under the assumption that $M_o \cong 2Z$. If this β was the same as the assumed β then the charge of the particle was considered to have been identified. If not, then one must repeat this procedure by successive approximations until the assumed β and the computed β agree to within statistical fluctuations.

Yet another procedure used by Freier was to again assume a value of β. This value of β was then substituted into equation (3-3), which was then solved for Z. Then it was assumed $M_o \cong 2Z$ so that one could then determine E from equation (3-5). If this value of R was the same as the measured R, then the particle was considered to be identified. If not, then one had to repeat this process until the proper value was obtained.

So far the above procedure has been used for those particles whose range ends in emulsion. When the impinging particle did not stop in the emulsion, these investigators determined some limits on the charge as follows:

First, the upper limit for the charge was obtained by assuming $\beta = 1$. This value of β was then substituted into the equation (3-3) along with the measured N_δ. This was then solved for Z. It should be clear that this is the upper limit for Z because this is the largest value that β can have.

The lower limit for the charge number Z was obtained by assuming that the range in the emulsion was the total range. Then with $M_o \cong 2Z$, the equations (3-3) and (3-4) were solved for Z. This is the lower limit for Z because the assumption that the R in the emulsion is the residual range makes E its smallest possible value as can be seen from the equation (3-4).

Based on the computations made in 1929 by Mott[1], Ashkin showed that the expression for dN_δ could be written as,

$$dN_\delta = \frac{2\pi N Z^2 e^4}{M_e \beta^2 c^2} \frac{dE'}{E'^2} \left\{ 1 - \tfrac{1}{2}(1-\beta^2)\left(\frac{E'}{M_e c^2}\right)\left(\frac{\pi 2\beta}{137}\right)\left[\tfrac{1}{2}\left(\frac{1-\beta^2}{\beta^2}\right)\left(\frac{E'}{M_e c^2}\right)\right]^{\frac{1}{2}} + \left[1 - \tfrac{1}{2}\left(\frac{1-\beta^2}{\beta^2}\right)\left(\frac{E'}{M_e c^2}\right)\right]\right\}$$

[1]H. L. Bradt and B. Peters, Phys. Rev. 74, 1828 (1948).

where the quantities of this equation are the same as they were previously defined.

According to Bradt and Peters[1], the term in the brace differs from unity by only eight percent. Since 8% is negligible, one may write

$$dN_{\delta} = \frac{2\pi NZ^2 e^4 \, dE'}{M_e \beta^2 c^2 E'^2} \qquad (3\text{-}6)$$

which is just the classical Rutherford expression. The essential difference between the work of Bradt[2] and Freier[3] is that different counting criteria were used. Bradt and Peters required that the delta rays exhibit four grains in a row before being counted. This is the so-called four-grain criterion and corresponds to a lower limit on the delta rays of about ten Kev., which is the same as that used by Freier. Since Bradt and Peter also used Ilford C-2 plates, then they had the same upper limit E'_m. The difference between this criterion and the one used by Freier, according to George[4], is that it is more subjective than the range criterion.

Next, S. O. C. Sorensen[5] points out that, in principle, it is possible to identify the charge of a particle by comparing the maximum value of its delta ray density with the maximum delta ray density of a

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[1]*Ibid.*

[2]*Ibid.*

[3]*Loc. cit.*

[4]E. C. George, Proc. Roy. Soc. 66A 1019 (1953).

[5]S. O. C. Sorensen, Phil. Mag. 40, 947 (1949).

known particle. To see this, consider the following:

First the Rutherford equation gives

$$dN_\delta = \frac{2\pi NZ^2e^4}{M_e v^2}\frac{dE'}{E'^2}$$

so

$$N = \int_{E_1'}^{E'_m} \frac{2\pi NZ^2e^4}{M_e v^2}\frac{dE'}{E'^2}$$

Considering the emulsion for which $E'_m = 2M_e v^2$, one obtains

$$N_\delta = \frac{2\pi Ne^4Z^2}{M_e v^2}\left(\frac{1}{E_1'} - \frac{1}{2M_e v^2}\right) \qquad (3\text{-}7)$$

which reveals that N_δ is a function of E_1'; N_δ is also subject to statistical fluctuations. Next, by the methods of differential calculus, one may find the value of $v = \beta c$ for which N_δ is a maximum as follows:

First differentiating equation (3-7) with respect to v, and equating the result to zero, one has

$$\frac{\delta N_\delta}{\delta v} = \frac{-4\, Ne^4Z^2}{M_e v^3}\left(\frac{1}{E_1'} - \frac{1}{2M_e v^2}\right) + \frac{2\pi Ne^4Z^2}{M_e v^2}\left(\frac{1}{M_e v^3}\right) = 0$$

which simplifies to

$$-\frac{2}{v}\left(\frac{1}{E_1'} - \frac{1}{2M_e v^2}\right) + \frac{1}{M_e v^3} = 0. \qquad (3\text{-}8)$$

After collecting terms one has

$$\frac{1}{M_e v^2} - \frac{1}{E_1'} = 0. \qquad (3\text{-}9)$$

Solving equation 9 for v one has

$$v = \pm\sqrt{\frac{E_1'}{M_e}}\ .$$

Substituting this value of v into the expression for N_δ one has

$$N_\delta^{max} = \frac{2\pi N e^4 Z^2}{M_e\ E_1'/M}\left(\frac{1}{E_1'} - \frac{1}{2M_e\left(E_1'/M_e\right)}\right) \qquad (3\text{-}10)$$

which simplifies to

$$N_\delta^{max} = \frac{Ne^4Z^2}{E_1'}\left(\frac{1}{E_1'} - \frac{1}{2E_1'}\right)$$

and, after collecting terms, one has

$$N_\delta^{max} = \frac{Ne^4Z^2}{E_1'^{\,2}}\ . \qquad (3\text{-}11)$$

This expression enables one to use the maximum value of the delta ray density to identify the charge of a particle. This identification may be done as follows:

First, consider equation (3-11) for a known particle, and then for an unknown particle and take the ratio of the two equations so obtained, in which case one has

$$\frac{N_\delta^{max}{}_k}{N_\delta^{max}{}_u} = \frac{Z^2{}_k}{Z^2{}_u} \qquad (3\text{-}12)$$

where the subscript k and u refer to the known and unknown particles respectively. This can immediately be solved for Z_u to obtain

$$Z_u = Z_k\sqrt{\frac{N_\delta^{max}{}_u}{N_\delta^{max}{}_k}} \qquad (3\text{-}13)$$

To facilitate the use of this method it would be useful to have the batch of emulsions calibrated by plotting curves of N_δ versus residual range R for known particles and recording the maximum values of N_δ^{max}; and, then make similar plots for the particles under analysis and compare these as indicated by equation (3-13). There is one drawback to the use of this method. The maximum value of N_δ occurs near the end of the residual range of the particle in the emulsion. This would require for all practical purposes that one has a particle nearing the end of its residual range. For many of the interesting cases, though, this is not the case. Also, this expression for N_δ^{max} is subject to the ordinary statistical fluctuations, which are usually in the neighborhood of about ten percent.

Sorensen[1] also investigated the variation in the delta ray density N_δ as a function of the residual range for particles of various charges. This has turned out to be particularly useful in estimating the limits on the charge for particles with residual ranges in the region of a few hundred microns as is usually found in hyperfragment tracks. To make use of these one plots N_δ as a function of R on a graph like the one in Fig. 16. One then compares this curve to the known curves and this will indicate usually the limits on Z.

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[1] *Ibid.*

CHAPTER IV

A CURIOUS COSMIC RAY EVENT

Introduction

A portion of a small stack of four-hundred-micron Ilford G-5 pellicles that was exposed to the cosmic radiation[1] at an altitude of 93,000 ft., has been scanned. In this stack a curious event was found. A photomosaic of the event is shown in Fig. 6. In the photomosaic, S represents the center of a ten prong star. $\overline{SY}$ represents the track of a particle that emanated from the star and it will be referred to as particle number 3. This particle traveled a distance of 1453 microns in the emulsion to the point Y, whereupon it split into two tracks, $\overline{YR}$ (hereafter called particle number 2), and $\overline{YB}$ (hereafter referred to as particle number 1). Particle 2 has a residual range of 1674 microns. Particle number 1 traveled a distance of 293 microns to the point B, where it was either scattered laterally into the thin layers of tissue paper which separated it from the next pellicle in the stack, or it proceeded into the next emulsion. It could not be traced into the next pellicle, although the measurements indicated that it possessed sufficient energy to penetrate into this emulsion if it were a K-meson or

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[1]Flown by the "Project Skyhook", courtesy of the Office of Naval Research.

Fig. 6-- Photomosaic of the Y-Event

lighter. None of the three tracks were steeply dipping in the unprocessed emulsion[1].

Discussion

A check was made to determine if the three tracks were coplanar in the neighborhood of the Y-vertex. An angle of $89^{\circ}\ 40' \pm 49'$ was found between the normal to the plane of tracks 1 and 2 and the direction of track 3 at the Y-vertex. Next, the angles $\theta_{1,3}$ and $\theta_{2,3}$ between the directions of particle 1 and 3 and particles 2 and 3 were found to be $30^{\circ}\ 31 \pm 40'$ and $18\ \ 25' + 7'$, respectively. Finally, the mass of particle 3 was estimated by means of constant cell-length scattering. The data for this are shown in Table 1. The gap-density versus the available residual range for this particle is shown in Fig. 7.

To estimate the mass of particle 1, the constant cell-length multiple-scattering was used along with the gap-density at the center of this track. The multiple-scattering data are shown in Table 2. These were checked for consistency by comparing the change in gap-density of this track with that of the proton tracks. The gap-density versus the residual range for the calibration tracks 1, 2 and 3, along with the average for these three tracks is shown in Figs. 8, 9, 10 and 11, respectively; whereas, that for particle 1 is shown in Fig. 12. The location of the three calibration tracks is shown in Table 3.

The mass of particle 2 was first estimated by using a Biswas $P_{0.5}$ scattering scheme[2]. The data for this are shown in Table 4. The con-

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[1]This is mentioned because corrections for distortion were not made.

[2]Fitzpatrick, loc. cit.

TABLE 1

SCATTERING DATA FOR PARTICLE 3 IN THE Y-EVENT

β_{sd}	y_{sd}	$S_{pd}^{\lambda} = 15$	$D_{sd}^{\lambda} = 15$
5	0.0	1.0	0.7
5	-0.2	0.9	0.7
5	-0.3	0.8	0.4
5	-0.4	0.8	0.5
5	-0.5	0.7	0.5
5	-0.6	0.5	0.2
5	-0.7	0.5	0.4
5	-0.7	0.4	0.0
5	-0.8	0.5	0.4
5	-0.8	0.5	0.3
5	-0.9	0.3	0.0
5	-0.9	0.4	0.3
5	-1.0	0.2	0.0
5	-0.9	0.5	0.4
5	-1.0	0.4	0.2
5	-1.0	0.3	0.0
5	-1.1	0.2	-0.2
5	-1.1	0.4	0.3
5	-1.2	0.3	0.1
5	-1.2	0.2	-0.1
5	-1.1	0.3	0.1
5	-1.2	0.1	-0.3
5	-1.1	0.4	0.1
5	-1.3	0.1	-0.4
5	-1.3	0.2	-0.1
5	-1.2	0.3	-0.1
5	-1.3	0.1	-0.4
5	-1.2	0.2	-0.4
5	-1.4	0.1	-0.4
5	-1.4	0.2	-0.2
5	-1.3	0.3	-0.1
5	-1.3	0.4	0.0
5	-1.5	0.1	-0.4
5	-1.5	0.2	-0.2
5	-1.4	0.3	-0.2
5	-1.4	0.2	-0.5
5	-1.3	0.4	-0.2
5	-1.5	0.3	-0.3
5	-1.4	0.5	-0.1
5	-1.5	0.3	-0.5
5	-1.5	0.4	-0.3

TABLE 1 - Continued

β_{sd}	y_{sd}	$S_{pd}^{\lambda=15}$	$D_{sd}^{\lambda=15}$
5	-1.4	0.5	-0.2
5	-1.4	0.6	0.0
5	-1.5	0.5	-0.2
5	-1.6	0.4	-0.3
5	-1.6	0.4	-0.4
5	-1.7	0.4	-0.3
5	-1.6	0.5	-0.2
5	-1.7	0.4	-0.4
5	-1.7	0.5	-0.2
5	-1.6	0.7	0.1
5	-1.7	0.6	0.1
5	-1.8	0.6	0.3
5	-1.9	0.6	0.3
5	-1.8	0.8	0.7
5	-1.9	0.7	0.6
5	-1.9	0.7	0.5
5	-2.0	0.6	0.5
5	-2.0	0.7	0.7
5	-2.0	0.7	0.7
5	-2.0	0.8	0.9
5	-2.1	0.7	0.7
5	-2.1	0.7	0.7
5	-2.1	0.8	0.8
5	-2.2	0.7	0.7
5	-2.3	0.6	0.5
5	-2.3	0.5	0.2
5	-2.4	0.3	-0.1
5	-2.5	0.3	0.0
5	-2.6	0.1	-0.5
5	-2.6	0.1	-0.4
5	-2.6	0.2	-0.3
5	-2.6	0.1	-0.6
5	-2.7	0.0	-0.7
5	-2.7	0.0	-0.9
5	-2.8	-0.1	-1.0
5	-2.8	0.0	-0.7
5	-2.8	0.0	-0.9
5	-2.9	0.0	-0.9
5	-2.9	0.0	-0.9
5	-2.9	0.1	-0.8
5	-2.8	0.3	-0.5
5	-2.7	0.4	-0.4
5	-2.8	0.3	-0.5

TABLE 1 - Continued

β_{sd}	y_{sd}	$S_{pd}^{\lambda=15}$	$D_{sd}^{\lambda=15}$
5	-2.7	0.6	-0.1
5	-2.7	0.5	-0.3
5	-2.8	0.5	-0.3
5	-2.7	0.7	0.0
5	-2.7	0.8	0.2
5	-2.7	0.9	0.3
5	-2.7	0.9	0.3
5	-2.8	0.7	0.1
5	-2.8	0.9	0.5
5	-2.9	0.9	0.5
5	-2.9	0.9	0.5
5	-3.0	0.9	0.5
5	-3.1	0.8	0.4
5	-3.1	0.8	0.5
5	-3.1	0.8	0.6
5	-3.3	0.7	0.4
5	-3.2	0.8	0.5
5	-3.3	0.8	0.5
5	-3.4	0.7	0.4
5	-3.5	0.6	0.1
5	-3.6	0.6	0.1
5	-3.6	0.6	0.1
5	-3.5	0.6	-0.1
5	-3.7	0.4	-0.3
5	-3.8	0.4	-0.2
5	-3.8	0.4	-0.4
5	-3.9	0.4	-0.4
5	-3.9	0.4	-0.6
5	-3.9	0.3	-0.8
5	-3.9	0.2	-1.1
5	-4.0	0.3	-0.8
5	-4.0	0.3	-0.8
5	-4.1	0.3	-0.9
5	-4.1	0.3	-1.0
5	-4.1	0.5	-0.6
5	-4.2	0.5	-0.5
5	-4.2	0.5	-0.6
5	-4.1	0.7	-0.3
5	-4.1	0.7	-0.2
5	-4.2	0.6	-0.4
5	-4.2	0.8	-0.1
5	-4.3	0.8	-0.1
5	-4.3	1.0	0.4

TABLE 1 - Continued

β_{sd}	y_{sd}	$S_{pd}^{\lambda=15}$	$D_{sd}^{\lambda=15}$
5	-4.2	1.1	0.4
5	-4.1	1.3	0.6
5	-4.3	1.1	0.4
5	-4.3	1.1	0.2
5	-4.4	1.2	0.5
5	-4.4	1.3	0.6
5	-4.6	1.1	0.3
5	-4.7	1.0	0.2
5	-4.7	1.1	0.3
5	-4.8	1.0	0.1
5	-4.8	0.9	-0.2
5	-4.8	1.0	-0.1
5	-5.0	0.9	-0.1
5	-5.1	0.9	-0.1
5	-5.3	0.6	-0.7
5	-5.3	0.7	-0.6
5	-5.4	0.7	-0.5
5	-5.4	0.7	-0.8
5	-5.4	0.9	-0.5
5	-5.6	0.7	-0.8
5	-5.7	0.7	-0.6
5	-5.7	0.8	-0.7
5	-5.7	0.8	-0.7
5	-5.8	0.8	-0.8
5	-5.8	0.9	-0.7
5	-5.7	1.1	-0.5
5	-5.9	1.0	-0.7
5	-6.0	1.0	-0.8
5	-5.9	1.3	-0.4
5	-6.0	1.3	-0.4
5	-6.1	1.2	-0.8
5	-6.1	1.5	-0.3
5	-6.3	1.4	-0.4
5	-6.3	1.5	-0.4
5	-6.4	1.3	-0.7
5	-6.5	1.5	-0.4
5	-6.5	1.5	-0.6
5	-6.6	1.6	-0.3
5	-6.7	1.6	-0.4
5	-6.8	1.6	-0.3
5	-6.9	1.5	-0.6
5	-6.9	1.7	-0.3

TABLE 1 - Continued

β_{sd}	γ_{sd}	$S_{pd}^{\lambda=15}$	$D_{sd}^{\lambda=15}$
5	-7.0	1.8	-0.2
5	-7.2	1.7	-0.2
5	-7.3	1.7	-0.3
5	-7.3	2.0	
5	-7.6	1.8	
5	-7.7	1.8	
5	-7.8	1.9	
5	-7.7	2.0	
5	-8.0	1.9	
5	-8.0	2.1	
5	-8.2	1.9	
5	-8.3	2.0	
5	-8.4	1.9	
5	-8.4	2.1	
5	-8.6	2.0	
5	-8.8	2.0	
5	-8.9	1.9	
5	-9.0	2.0	
5	-9.3		
5	-9.4		
5	-9.5		
5	-9.7		
5	-9.7		
5	-9.9		
5	-10.1		

$$D_{sd}^{\lambda=15} = \frac{70.9}{173} = 0.410 \text{ scale divisions}$$

$$D^{\lambda=15} = 0.586 \text{ microns}$$

$$D_{N}^{\lambda=15} = 0.23 \text{ microns}$$

$$D_{ob}^{\lambda=15} = \left(0.586^{2} - 0.23^{2}\right)^{\frac{1}{2}} = \left(0.343 - 0.053\right)^{\frac{1}{2}} = \left(0.29\right)^{\frac{1}{2}} .$$

This yields $M_3 = 5706 \pm 2900$, if $Z = 1$ and $M_3 = 1899 \pm 850$, if $Z = 2$.

β_{sd} is cell length in scale divisions where one scale division equals 1.43 microns.

TABLE 1 - Continued

y_{sd} is measured coordinate in scale divisions

$S_{sd}^{\lambda} = 15$ is the first difference in scale divisions for an overlap of fifteen cell lengths.

$D_{sd}^{\lambda} = 15$ is the second difference in scale divisions for an overlap of fifteen cell lengths.

This is followed in each constant cell length scattering measurements.

1 scale division = 1.43 microns.

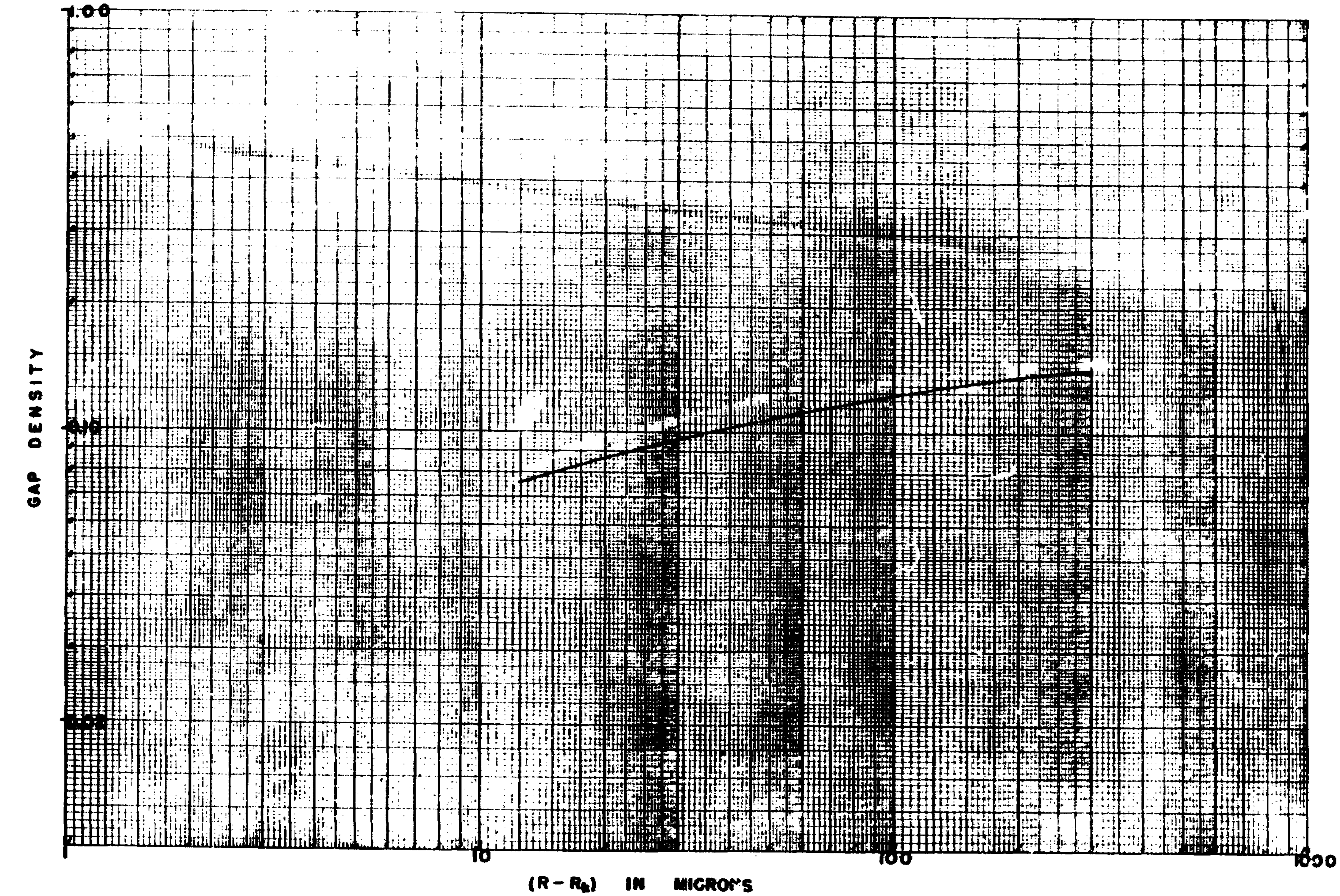

Fig. 7 -- Gap density versus the available residual range for particle 3

TABLE 2

SCATTERING DATA FOR PARTICLE 1 IN THE Y-EVENT

β^{i}_{sd}	y_{sd}	$S_{sd}^{\lambda = 5}$	$D_{sd}^{\lambda = 5}$
0	-2	-1.0	0.8
5	-1.9	-1.1	0.5
5	-1.5	-1.0	0.4
5	-1.3	-1.2	-0.1
5	-1.1	-1.4	-0.6
5	-1.0	-1.8	-1.4
5	-0.8	-1.6	-1.1
5	-0.5	-1.4	-0.9
5	-0.1	-1.1	-0.8
5	0.3	-0.8	-0.6
5	0.8	-0.4	-0.2
5	0.8	-0.5	-0.4
5	0.9	-0.5	-0.4
5	1.0	-0.3	-0.2
5	1.1	-0.2	0.0
5	1.2	-0.2	-0.1
5	1.3	-0.1	0.1
5	1.4	0.1	0.3
5	1.3	0.1	0.5
5	1.3	-0.2	0.2
5	1.4	-0.1	0.3
5	1.4	-0.2	0.2
5	1.3	-0.4	-0.1
5	1.2	-0.6	-0.3
5	1.5	-0.4	-0.1
5	1.5	-0.4	0.0
5	1.6	-0.4	0.0
5	1.7	-0.3	0.3
5	1.8	-0.3	0.2
5	1.9	-0.3	0.1
5	1.9	-0.4	-0.2
5	2.0	-0.4	
5	2.0	-0.6	
5	2.1	-0.5	
5	2.2	-0.4	
5	2.3	-0.2	
5	2.4		
5	2.6		
5	2.6		
5	2.6		
5	2.5		

TABLE 2 - Continued

$\lambda = 5$ indicates that a coefficient of overlap of 5 was used.

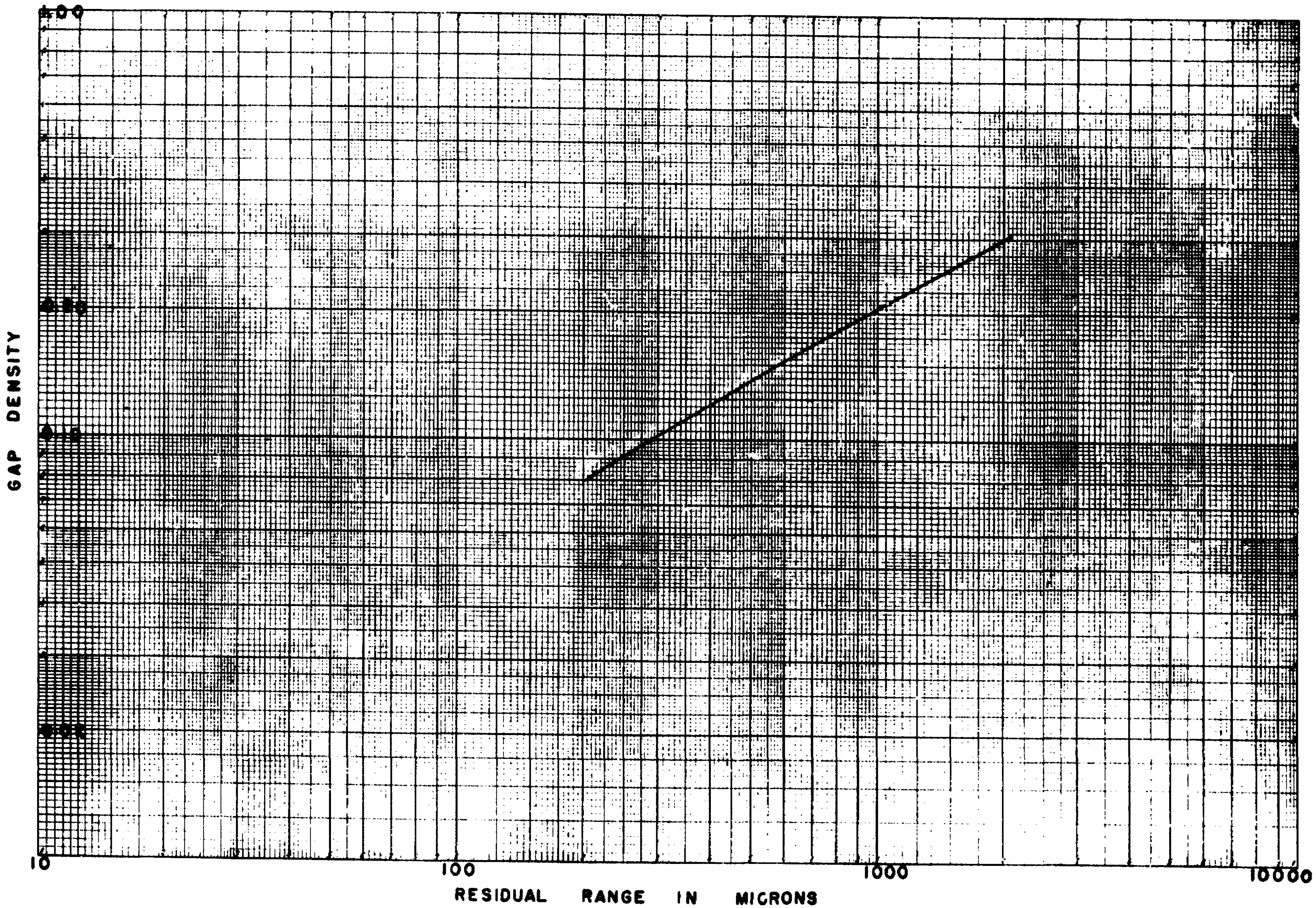

Fig. 8-- Gap density versus residual range for proton calibration track number 1

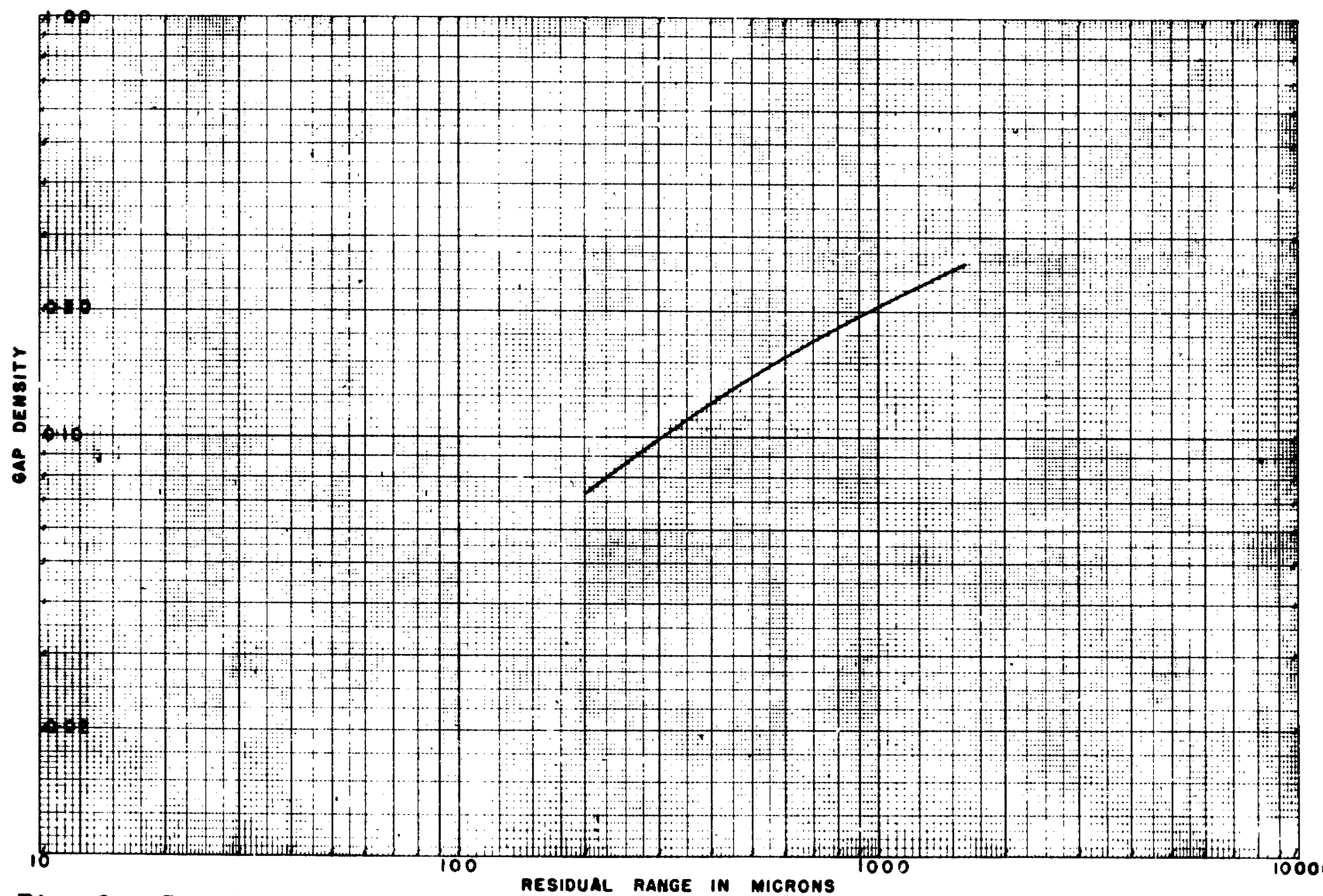

Fig. 9-- Gap density versus residual range for proton calibration track number 2.

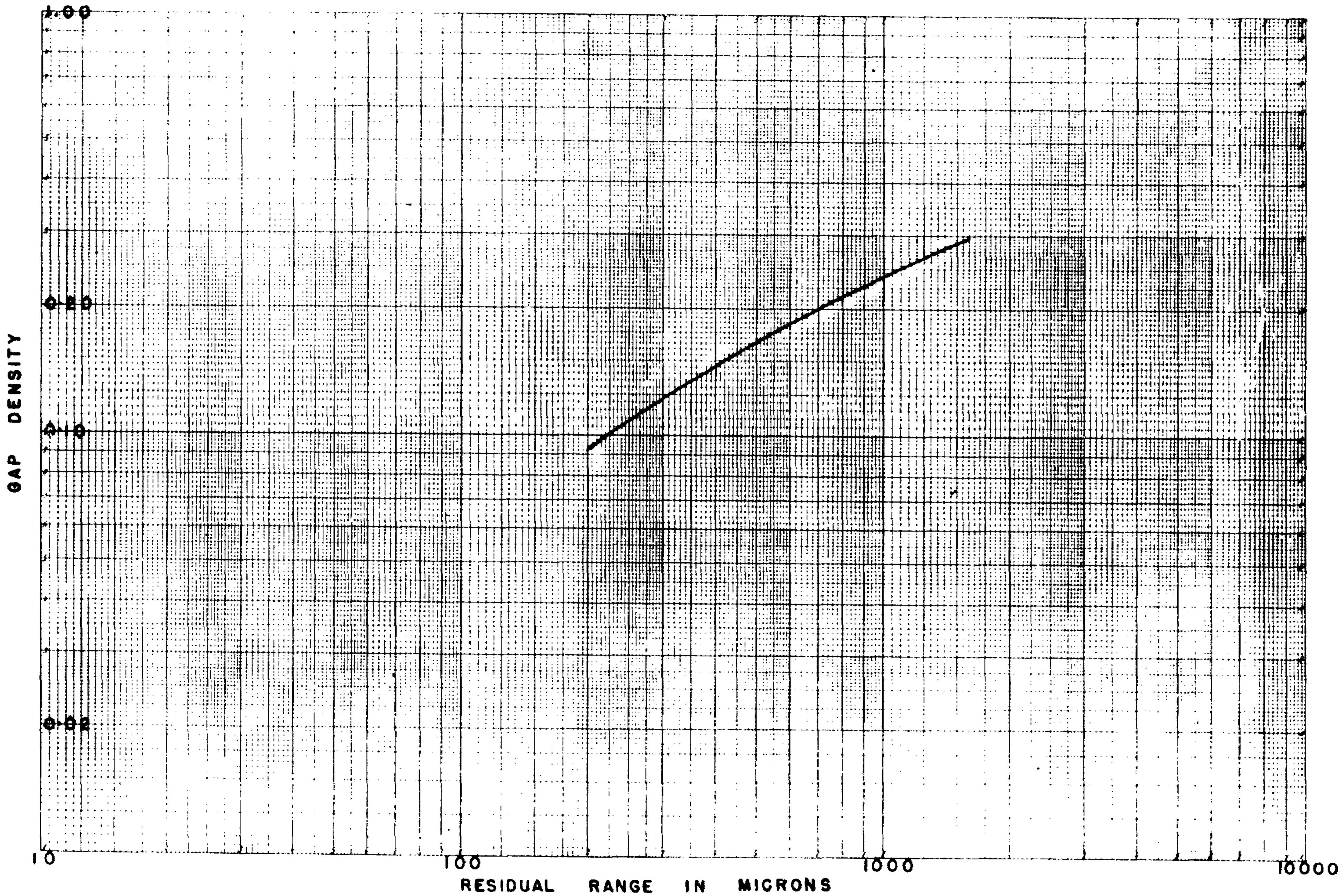

Fig. 10 -- Gap density versus residual range for proton calibration track number 3

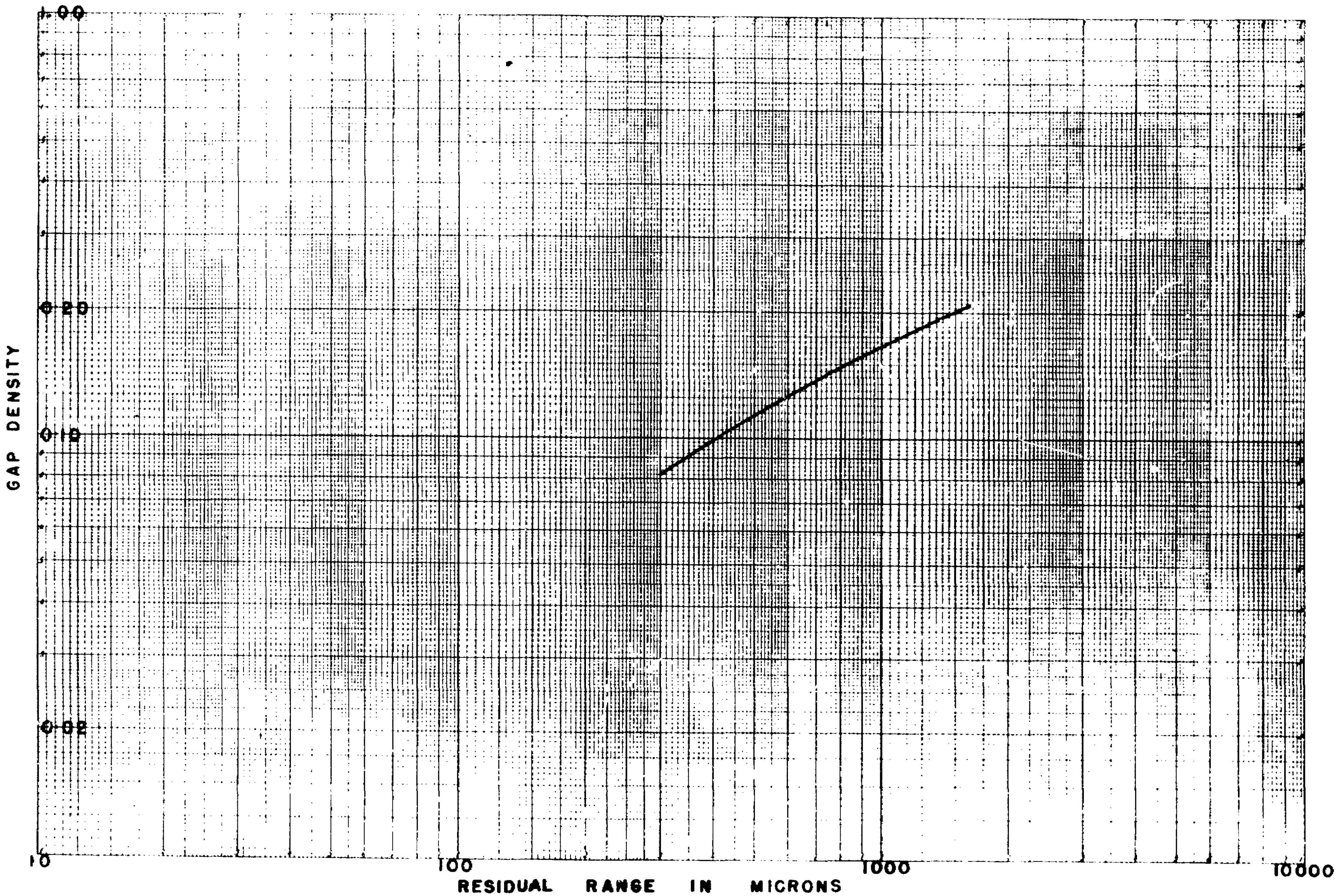

Fig. 11-- Gap density versus residual range for the average proton calibration track

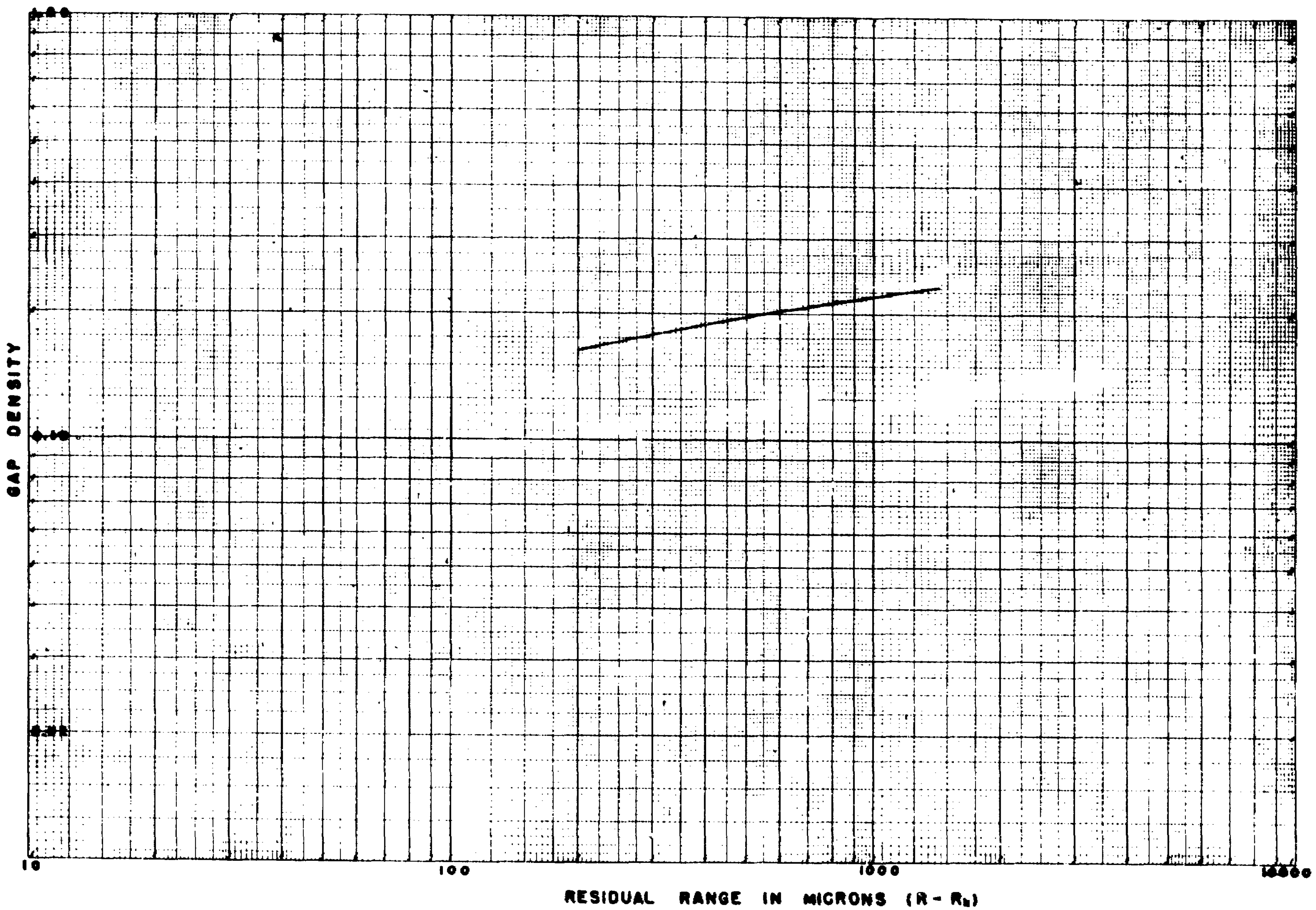

Fig. 12-- Gap density versus the available residual range for particle #1.

TABLE 3

LOCATION OF TRACKS THAT WERE USED IN GAP COUNT CALIBRATIONS

Emulsion Number	Date of Exposure	Length of Track	Coordinates of Endpoints on Spencer Research Microscope	Appearance of Particle
1	1-18-55	18,000 microns	44.2;97.8	proton
9	1-18-55	9,000 microns	54.5;94.6	proton
2	1-18-55	7,000 microns	43.5;90.9	proton

TABLE 4

$P_{0.5}$ SCATTERING DATA FOR PARTICLE NUMBER 2

ΔR_{sd}	y_{sd}	S_{sd}	D_{sd}
0	0.0	-0.4	0.2
4	0.1	-0.6	0.2
5	0.4	-0.6	0.5
5	0.7	-0.8	0.6
5	1.0	-1.1	1.1
6	1.5	-1.4	1.2
6	2.1	-2.2	0.0
7	2.9	-2.6	-0.4
7	4.3	-2.2	-0.2
7	5.4	-2.2	-0.5
7	6.5	-2.0	-0.3
8	7.6	-1.7	+0.2
8	8.5	-1.7	+0.8
8	9.3	-1.9	+1.0
8	10.2	-2.5	0.0
9	11.2	-2.9	-0.9
9	12.7	-2.5	-0.8
9	14.1	-2.0	-0.6
9	15.2	-1.7	-0.5
10	16.1	-1.4	-0.3
9	16.9	-1.2	-0.3
11	17.5	-1.1	-0.3
10	18.1	-0.9	-0.2
10	18.6	-0.8	-0.1
9	19.0	-0.7	-0.1
12	19.4	-0.7	-0.1
10	19.7	-0.6	0.1
12	20.1	-0.6	-0.4
10	20.3	-0.7	-0.6
13	20.7	-0.2	0.2
11	21.0	-0.1	0.2
13	20.9	-0.4	-0.2
17	21.1	-0.3	0.3
14	21.3	-0.2	0.9
11	21.4	-1.6	0.3
14	21.5	-1.1	-0.1
11	22.0	-0.9	-0.1
14	22.6	-1.0	-0.8
12	22.9	-0.8	-0.7
15	23.6	-0.2	-0.3

TABLE 4 - Continued

ΔR_{sd}	y_{sd}	S_{sd}	D_{sd}
12	23.7	-0.1	0.1
15	23.8	0.1	0.4
12	23.8	-0.2	-0.4
16	23.7	-0.3	-0.9
13	24.0	0.2	-0.8
16	24.0	0.6	-0.7
13	23.8	1.0	0.0
16	23.4	1.3	0.6
13	22.8	1.0	0.3
17	22.1	0.7	0.2
13	21.8	0.7	-0.3
17	21.4	0.5	-0.9
14	21.1	1.0	-0.3
17	20.9	1.4	-0.1
14	20.1	1.3	0.1
18	19.5	1.5	0.6
14	18.8	1.2	0.4
18	18.0	0.9	0.3
14	17.6	0.8	0.4
18	17.1	0.6	0.2
15	16.8	0.4	0.2
18	16.5	0.4	0.4
15	16.2	0.2	0.5
19	16.1	0.0	0.7
15	16.0	-0.3	0.8
19	16.1	-0.7	0.4
16	16.3	-1.0	0.2
19	16.8	-1.1	0.2
16	17.3	-1.2	0.1
19	17.9	-1.3	-0.2
16	18.5	-1.3	-0.8
20	19.2	-1.1	-1.4
16	19.8	-0.5	-0.7
20	20.3	0.3	0.6
17	20.3	0.2	0.5
20	20.0	-0.3	-0.1
17	20.1	-0.3	-0.1
20	20.3	-0.2	-0.1
17.2	20.4	-0.2	0.1
21	20.5	-0.1	-0.8
17	20.6	0.3	0.0
21	20.6	0.7	0.6
18	20.3	0.3	

TABLE 4 - Continued

ΔR_{sd}	y_{sd}	S_{sd}	D_{sd}
21	19.9	0.1	
18	20.0		
22	19.8		

These data yield a mass estimate of $M_2 = 1557 \pm 437\ M_{\odot}$

sistency of this estimate was then checked by using Perkin's method. The graphs of the total gap length versus the residual range for particle 2 and the three calibration protons are shown in Fig. 13.

The results of the mass estimates are summarized in Table 5.

Interpretation of the Event

Finally, the following three interpretations of the event have been considered:

1. An inelastic nuclear interaction involving particle 3 and an emulsion nucleus.

2. An elastic knock-on process involving particle 3 and a hydrogen atom.

3. The decay in flight of a doubly charged particle.

Although the first interpretation cannot be completely ruled out, the coplanarity of the three tracks in the neighborhood of the Y-vertex is suggestive that such an event did not occur.

Interpretation number 2 seems improbable because of the following argument: the gap-length measurements indicate that the gap-density of track 2 is greater than that for track 3 in the vicinty of the Y-vertex as can be seen in Fig. 14, which is a plot of the total gaps versus the residual range under the assumption that track 1 is a continuation of track 3. If this were an elastic "knock-on" one would expect the gap-density for track 3 to be greater than that for track 1. This plot clearly shows that just the reverse of this is true. Thus, if the event is to be interpreted as an elastic "knock-on" process involving a hydrogen atom, then particle 2 must be a proton and particle number 3 some

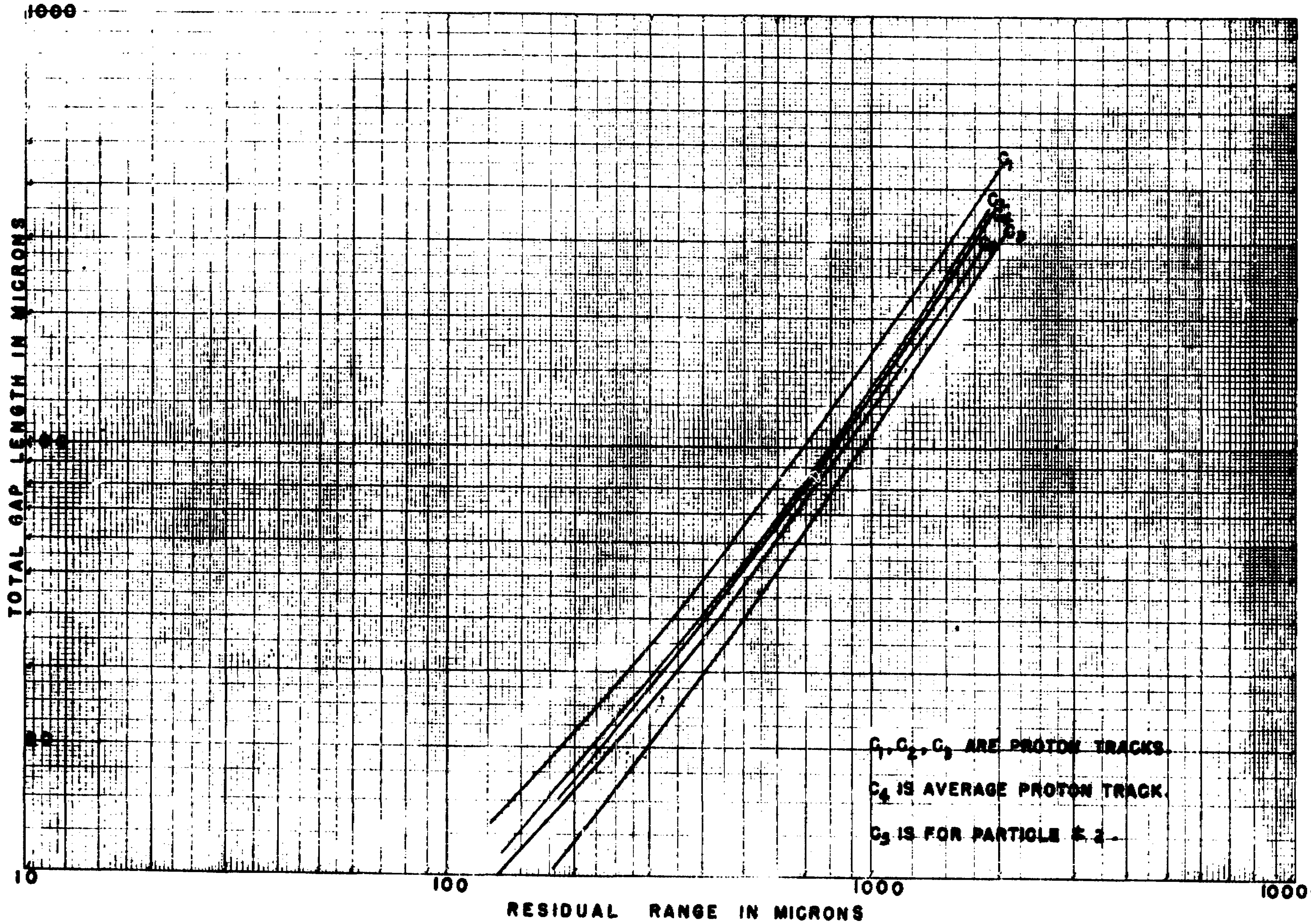

Fig. 13-- Total gap length versus the residual range for the three calibration tracks and for particle 2

PARTICLE	METHOD USED	RESULTS
1	CONSTANT CELL SCATTERING	1812 ± 1200 M_E
	CHANGE IN GAP DENSITY	2388 ± ?
2	CONSTANT SAGITTA SCATTERING	1557 ± 440
	PERKIN'S METHOD	1966 ± 360
3	CONSTANT CELL SCATTERING	5706 ± 2900 (Z = 1)
		1899 ± 850 (Z = 2)

Table 5. -- Summary of the mass estimates of the 3 particles in the event

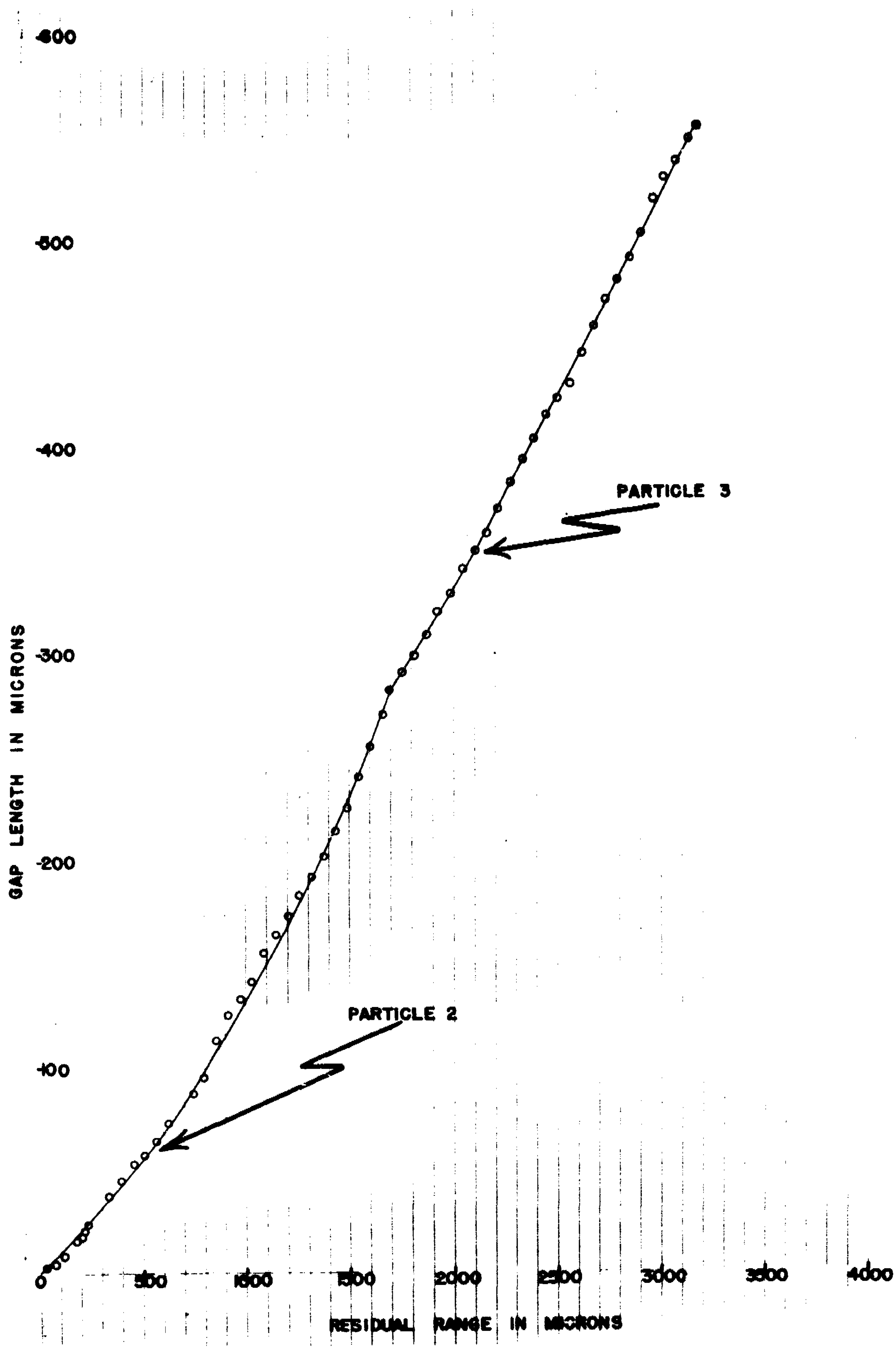

Fig. 14-- The gap length versus the residual range if particles 2 and 3 are identical

other particle. Consistent with this and with the mass estimates, assume that particle 2 is an elastic "knock-on" proton and that particles 1 and 3 are identical. From these assumptions[1] one may show that the mass of 1 (and therefore 3) is $m_1 = 3342 \pm 44M_e$. But a particle with this mass and with $Z \geqq 1$ would have far too much momentum to balance the transverse momentum of particle 2 even if it traveled only the visible 293 microns in the emulsion.

Since the first two interpretations appear unsatisfactory, then it appears that the third one is worthy of consideration, that is, that a doubly charged particle was emitted from the star and then decayed in flight at the Y-vertex into two singly charged particles.

As was seen in table 5 for the mass estimates, the measurements made on particle 2 are the most reliable. The mass estimates showed that this was most probably a proton. In the following discussion it will be assumed that this particle is a proton having an energy of 19.0 $\pm$ 0.4 Mev.

If one makes this assumption and invokes the laws of conservation of charge, momentum and energy, then one can determine the characteristics of particle 3 indirectly by direct measurements on particles 1 and 2. This procedure was followed for two reasonable assumptions for the mass of particle 1. The results are summarized in table 6 along with the results of some of the direct measurements on these tracks.

In table 6 scheme number 1 would correspond to an event of the

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[1] See APPENDIX A.

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[1] See APPENDIX A.

SCHEME	M_1 (M_E)	E_1 (MEV)	Q (MEV)	M_3 (M_E)	E_3 (MEV)
1	968	14.0 ± 0.3	4.2 ± 0.5	2812 ± 0.8	28 8 ± 0.2
2	1836	7.4 ± 0.2	4.4 ± 0 1	3681 ± 0.2	22.0 ± 0.5

THE VALUES LISTED ABOVE ARE CONSISTENT WITH THE ASSUMPTION THAT 2 IS A PROTON AND THE CONSERVATION LAWS HOLD. BELOW ARE THE MEASURED VALUES.

SCHEME	E_1 (MEV)	E_3 (MEV)	P_3 ($\frac{MEV}{C}$)	P''_{1+2} ($\frac{MEV}{C}$)	$R_{P''}$ ($\frac{MEV}{C}$)	$P_1^{\perp}$ ($\frac{MEV}{C}$)	$P_2^{\perp}$ ($\frac{MEV}{C}$)	$R_{P^{\perp}}$ ($\frac{MEV}{C}$)
1	5 7 ± 18	132 ± 29	609 ± 74	244 ± 74	76	38	59 3	6 3
2	10 9 ± 3 7	175 ± 40	1380 ± 82	302 ± 86	86	71	59.3	14

Table 6. -- The balance of the momenta for the 3 particles in the event

type $Y^{++} \rightarrow P+K^{+}+Q$; whereas, scheme number 2 would correspond to an event of the type $Y^{++} \rightarrow 2P+Q$. In either case the time of flight of particle 3 is about 10^{-11} sec.

Scheme one gives a better statistical agreement with the measured mass of particle 3 as well as with its energy and longitudinal momentum; whereas, scheme 2 gives better agreement with the balancing of the transverse momentum. But since the measurements made on particle 3 are somewhat more reliable than those made on particle 1, scheme 1 seems more acceptable.

If one assumed that the event described in scheme 1 did occur, then particle 3 would have a mass similar to that of the particle reported by Y. Eisenberg[1], but in a different charge state.

Conclusion

Because of the better statistical agreement, the author favors the interpretation given by scheme 1; namely, that it is an event of the type $Y^{++} \rightarrow P + K^{+} + Q$.

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[1] Y. Eisenberg, Phys. Rev. **96** (541) 1954.

CHAPTER V

A POSSIBLE HYPERFRAGMENT

In the photomosaic in Fig. 15 is shown a star from which emanated a charged particle which appeared to come rest at the point Y. At this point are the beginnings of 2 other tracks, one which comes to rest at the point R_1 and the other at the point R_2. From now on the particle which produced track $\overline{YR_1}$ will be called particle 1, that which produced track $\overline{YR_2}$ will be called particle 2, and that which produced $\overline{SY}$ will be called particle 3.

As was done by other investigators[1], the author tentatively assumed that particle 1 is a proton. A partial identification is then made for the other 2 particles. First, the emulsions were calibrated for delta rays. The results of this are shown in the plot of the delta ray density versus residual range in Fig. 16. On this same graph is plotted the same information for particle 2. The data points fall well within the singly charged particle group so that one can assert that its charge is 1. The statistics are so poor that a charge of 2 cannot be ruled out; however, a charge of 3 seems too high. Similarly in the same figure, the delta ray density for particle 3 seems to fall close to that

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[1] W. Fry, J. Schneps and M. Swami, Phys. Rev. 99, 1561 (1955).

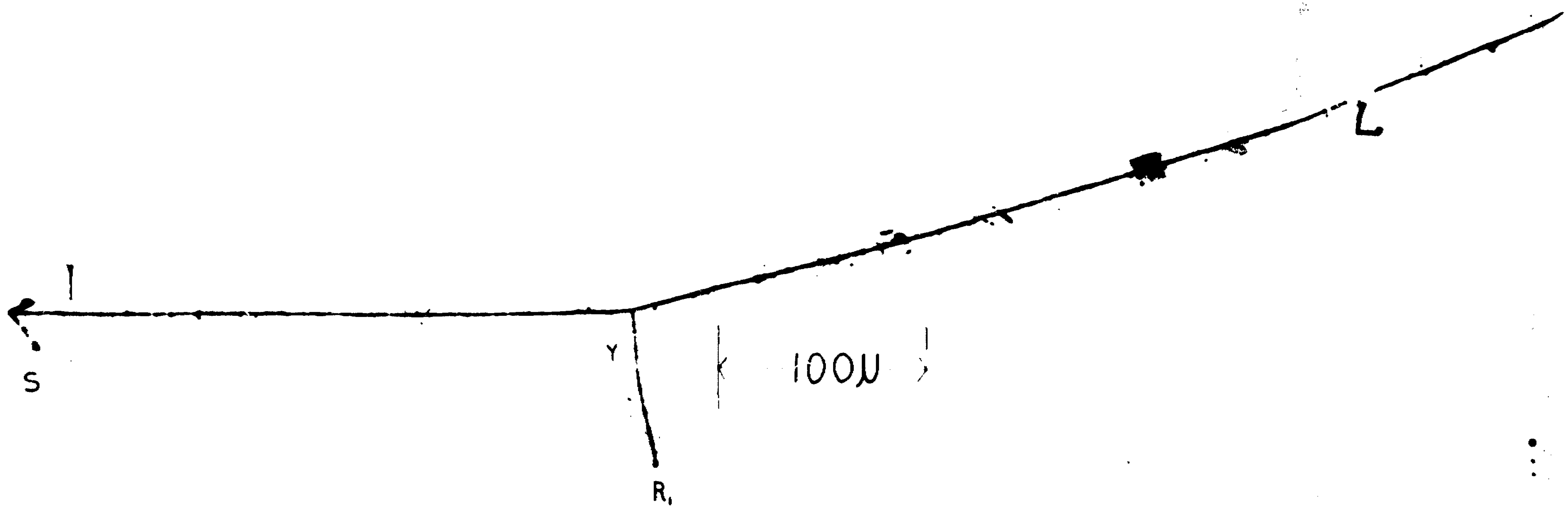

Fig. 15 -- A photomosaic of the hyperfragment. L is where particle 2 left emulsion 40 and entered emulsion 41.

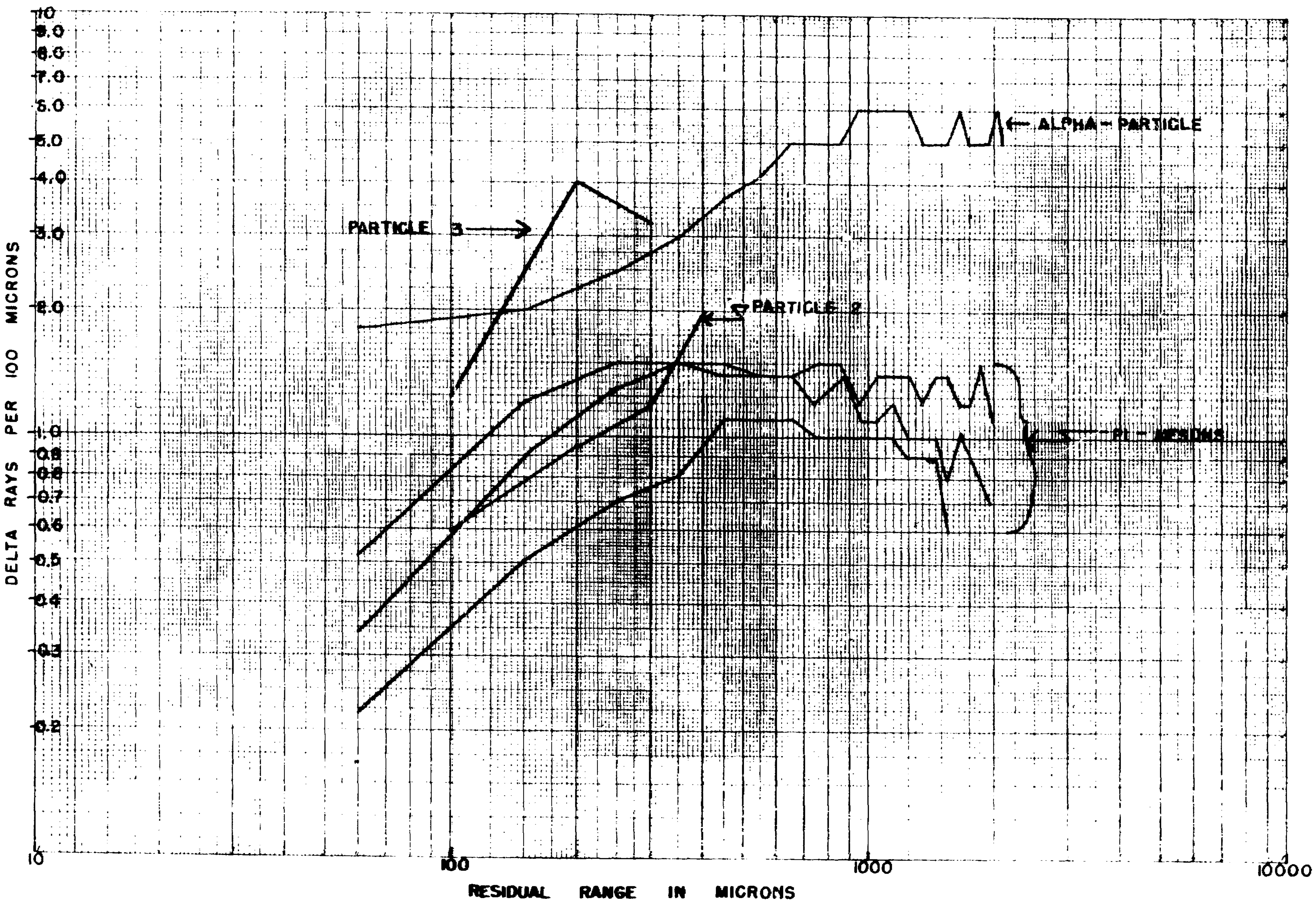

Fig. 16 -- Delta ray density versus the residual range in microns

for a particular alpha particle. Again then this would indicate the charge of particle 3 is perhaps 2 although due to the poor statistics and the small number of data points one would be reticient to say that this is not 3 or greater.

A systematic search was made of the region of the intersection of the 3 tracks for the evidence of an inelastic nuclear interaction. No such evidence was present. Next, the possibility of elastic interactions was checked and again no such possibility was found for the well known nuclei. This evidence coupled with the fact that particle 3 has the appearance of other multiply charged particles which came to rest in the emulsion leads one to the assumption that it came to rest.

If one makes the assumption that 3 came to rest it was apparent from the tracks of particles 1 and 2 that there was a residual momentum present. Since it has already been assumed 1 is a proton its momentum is readily found. Next, particle 2 was assigned a mass of various lighter nuclei consistent with its charge estimate, and its momentum was computed. Then from these two values one can compute the residual momentum for the two particles 1 and 2. The momentum could be balanced only if a ${}_{\Lambda}He^3$ fragment decayed according to the scheme

$$ {}_{\Lambda}He^3 \rightarrow P + D + \pi^0 + Q\left(34.6 \pm 1.8 \text{ Mev.}\right) $$

with $(B.E.)_{\Lambda^0} = 8.0 \pm 1.6$ Mev, unless one wishes to consider the possibility that more than one neutral particle was emitted in this decay. See appendix B for the computation of $(B.E.)_{\Lambda^0}$.

According to R. H. Dalitz[1] this value for (BE) is larger than

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[1]Private communication.

one might expect from the present theory of hyperfragments. He would favor an interpretation where 2 neutrons were emitted, thus increasing the Q-value and reducing $(BE)_{\Lambda^\circ}$. On the other hand, if particle 3 had only a short residual range at the intersection one could also make the momentum balance by assuming a decay in flight.

Various other isotopes of helium and lithium were considered but none was consistent with the fact that the particle from the star came to rest, and that the momentum is conserved only if one neutral particle takes part in this interaction.

Conclusion

Because the particle appears to come to rest and because one can balance the momentum by assuming that only one neutral particle was emitted in the decay, the author favors the interpretation given by the expression

$$_{\Lambda}He^3 \rightarrow P + D + \pi^\circ + Q(34.6 \pm 1.8 \text{ Mev.})$$

with

$$(B.E.)_{\Lambda^\circ} = 8.0 \pm 1.6 \text{ Mev.}$$

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A. THE RATIO OF THE MASSES OF TWO PARTICLES UNDERGOING AN ELASTIC COLLISION WHEN ONE IS INITIALLY AT REST

Consider the elastic interaction shown schematically in Fig. 17. Here a particle of mass M_1 and momentum P_1 impinges upon the particle of mass M initially at rest. Due to the collision, M_2 is given a momentum P_2 in the direction θ_2 and the particle of mass M_1 recoils with a momentum P_3 in the direction θ_1. Assuming that the interaction is non-relativistic one has for the conservation of momentum the equations

$$P_1^2 = P_2^2 + P_3^2 + 2P_2 \, P_3 \mathrm{Cos}\left(\theta_1 + \theta_2\right) \tag{A-1}$$

and

$$P_3 \sin \theta_1 = P_2 \sin \theta_2 \quad . \tag{A-2}$$

Since kinetic energy is conserved, one also has the equation

$$\frac{P_1^{\;2}}{M_1} = \frac{P_3^{\;2}}{M_2} + \frac{P_2^{\;2}}{M_2} \quad . \tag{A-3}$$

Solving equation (A-3) for $P_1^{\;2}$ one obtains

$$P_1^{\;2} = P_3^{\;2} + \frac{M_1}{M_2} P_2^{\;2} \quad . \tag{A-4}$$

Substituting this value of $P_1^{\;2}$ into (A-1) one obtains

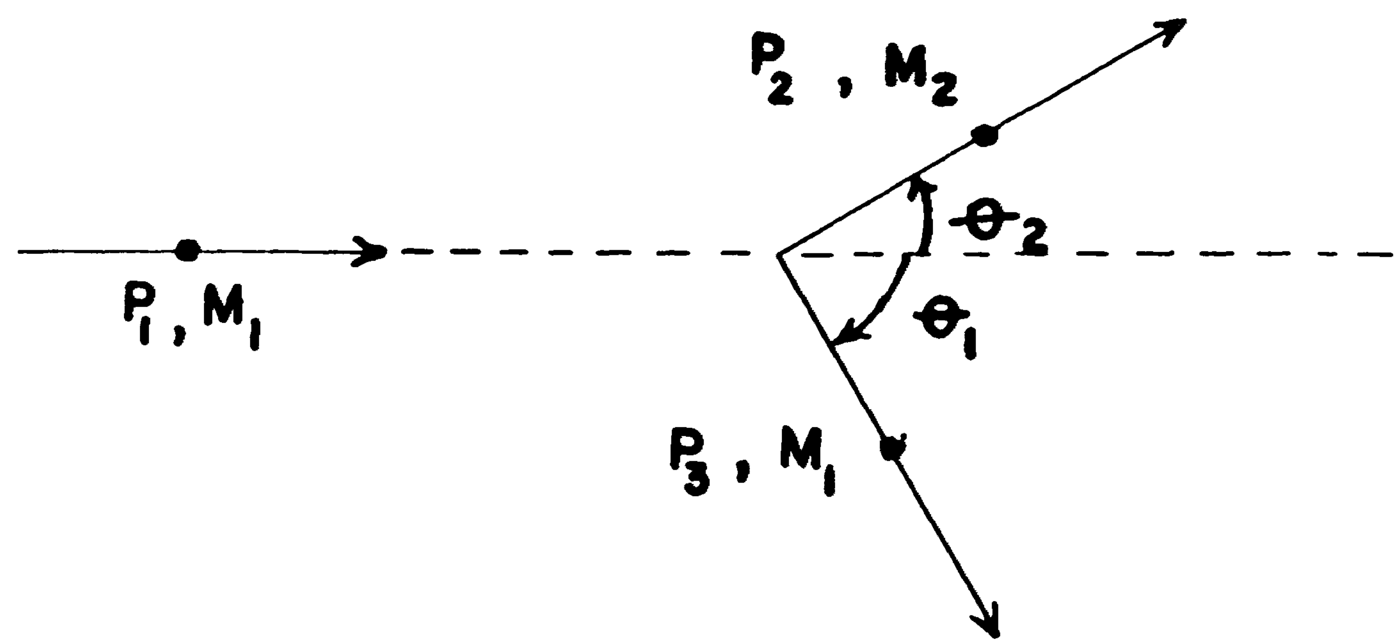

Fig. 17 -- A diagram to aid in computing the ratio of the masses of two particles in an elastic collision

$$\frac{M_1}{M_2} P_2^{\,2} = P_2^{\,2} \quad 2P_3\, P_2 \cos\left(\theta_1 + \theta_2\right). \tag{A-5}$$

But from equation (A-2) one has $P_3 = P_2 \dfrac{\sin\theta_2}{\sin\theta_1}$

which when substituted into equation (A-5) gives one the equation

$$\frac{M_1}{M_2} = 1 + \frac{2\sin\theta_2}{\sin\theta_1}\cos\left(\theta_1 + \theta_2\right). \tag{A-6}$$

Rearranging the R.H.S. of equation (A-6) one obtains

$$\frac{M_1}{M_2} = \frac{\sin\theta_1 + 2\sin\theta_2\left(\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2\right)}{\sin\theta_1}. \tag{A-6'}$$

Performing the indicated multiplication on the second term of the R.H.S. of equation (A-6′), after expansion of $\sin^2\theta_2$ and making use of the identity $2\sin\theta_2\cos\theta_2 = \sin 2\theta_2$, one has

$$\frac{M_1}{M_2} = \frac{\sin\theta_1 + \cos\theta_1\sin 2\theta_2 - 2\sin\theta_1 + 2\sin\theta_1\cos^2\theta_2}{\sin\theta_1}. \tag{A-7}$$

Simplifying equation (A-7) one obtains the result

$$\frac{M_1}{M_2} = \frac{\cos\theta_1\sin 2\theta_2 + \sin\theta\ \cos 2\theta_2}{\sin\theta_1}. \tag{A-8}$$

From equation (A-8) it follows immediately that

$$\frac{M_1}{M_2} \quad \frac{\sin\left(\theta_1 + 2\theta_2\right)}{\sin\theta_1}. \tag{A-9}$$

This equation gives the ratio of the masses of two particles that have collided elastically, in terms of the indicated trigonometric functions of the angles of recoil θ_1 and θ_2. This equation is very useful in deciding about the possible properties of colliding particles that one very often encounters in cosmic ray work.

B. A DERIVATION OF THE EXPRESSION FOR THE QUANTITY[1] Δ

By definition of the Q value for the spontaneous decay of a hyperfragment[1] one has

$$Q = M_{A^*,Z} - \sum M_i \qquad \text{(B-1)}$$

where M is the mass of the hyperfragment.[2]

A* is its mass number, Z is its atomic number and M_i is the mass if the i^{th} decay product. But from the definition of binding energy one has for the binding energy of the Λ^0 the following

$$(B.E.)_{\Lambda^0} = M_{A-1,Z} + M_{\Lambda^0} - M_{A^*,Z} \quad . \qquad \text{(B-2)}$$

Solving this equation for $M_{A^*,Z}$ and substituting this into equation (B-1) one obtains the equation

$$Q = M_{A-1,Z} + M_{\Lambda^0} - (B.E.)_{\Lambda} - \sum_i M_i \qquad \text{(B-3)}$$

Rearrangement of the terms in equation (B-3) gives

$$Q + \sum_i M_i = M_{A-1,Z} + M_{\Lambda^0} - (B.E.)_{\Lambda} \qquad \text{(B-3')}$$

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[1] As will be seen in the derivation, this is the difference between the binding energy of the "last neutron" in the nucleus and the binding energy of the Λ^0 in the hyperfragment.

[2] A hyperfragment is usually defined to be a nucleus which has a bound hyperon, according to Professor R. A. Howard who directed this research

Adding $M_N - M_N$, where M_N is the mass of the neutron, to the R. H. S. of equation (B-3) one obtains

$$Q + \sum_i M_i = M_{A-1,Z} + M_{\Lambda^0} - (B.E.)_{\Lambda^0} + M_N - M_N \quad . \tag{B-4}$$

But by definition of the binding energy $(B.E.)_N$ of the last neutron added to the nucleus, one has

$$(B.E.)_N = M_{A-1,Z} + M_N - M_{A,Z} \tag{B-5}$$

where $M_{A,Z}$ is the stable fragment corresponding to the hyperfragment $M_{A^*,Z}$.

Now equation (B-5) yields the result

$$M_{A-1,Z} = -M_N + M_{A,Z} + (B.E.)_N \tag{B-5'}$$

which when substituted into equation (B-4) yields

$$Q + \sum_i M_i = M_{A,Z} + (B.E.)_N + M_{\Lambda^0} - M_N - (B.E.) \quad . \tag{B-6}$$

Solving equation (B-6) for $(B.E.)_N - (B.E.)_{\Lambda^0}$ and calling this Δ one has

$$\Delta = \sum_i M_i + Q - M_{A,Z} - M_{\Lambda^0} - M_N \; . \tag{B-7}$$

Equation (B-7) is very useful in the study of hyperfragments. With Δ computed in terms of the quantities on the right together with the knowledge of $(B.E.)_N$, one can readily determine $(B.E.)_{\Lambda^0}$ and compare the two. It is believed that, if the notion that the hyperfragment is due to a nucleon being replaced by a hyperon, Δ should be quite small.