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VELOCITY DEPENDENCE OF TRACK DENSITY IN PROPANE AND HYDROGEN BUBBLE CHAMBERS

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Abstract

A study of ionization data for charged particles has been made in an underexpanded propane and a normally operated hydrogen bubble chamber. The gap-length distribution is found to be exponential over a wide range of velocity intervals, and the coefficient of this distribution gives a measure of the true track density, g; g is proportional to β^{-n}, where $n = 1.71 \pm 0.11$ for propane and $n = 1.86 \pm 0.37$ for hydrogen. The density of gaps, G, or of blobs, B, defined with good objective criteria, shows a dependence on g, namely $G(\epsilon) = g \exp[-g(a + \epsilon)]$; it passes through a maximum value, the position of which is related to the minimum resolvable gap distance (approximately the average diameter of individual bubbles).

The mechanisms of energy loss or δ-ray formation for the process of bubble nucleation have been discussed in view of these measurements. We find the track density g to be approximately proportional to the rate of energy loss, dE/dX; this would indicate that the bubble nucleation process may not be as simple as has been considered so far.

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I. Introduction

The ionization data on the charged particles passing through bubble chambers have rarely been used in the track evaluation because of the large variation of the operating conditions. It nevertheless has been helpful in some cases, such as in the identification of rare events.[1] However, the operating conditions have been improving, and the track evaluation by this method seems to be more promising. Therefore a systematic study of the problem under the present operating conditions would be worth while.

II. Track-Density Evaluation

In referring to ionization, the following nomenclature is relevant: (a) true bubble density, (b) blob or gap density. The "true bubble density" is defined as having a one-to-one correspondence to the density of the "thermal spikes" produced by the ionizing particle, which would lead to the formation of bubbles. Blobs are the isolated islands of bubble images separated by a minimum resolvable distance, and may have different sizes due to clogging of a number of bubbles. Also the gaps are counted only when they exceed a resolvable unit of length.

A number of observers[2] have used the method of counting bubbles per unit length as a measurement of specific ionization. This would underestimate the true bubble density because of losses due to limited optical resolution and possible bubble coalescence. Moreover, this method is somewhat subjective and involves the problem of reproducibility of the measurements. A really objective method is needed. The least subjective method seems to be the determination of the mean gap length from its distribution, which is extensively used in nuclear emulsion technique.

In nuclear emulsion, it was experimentally shown by O'Cealaigh[3] that the gap distribution is exponential. The gap distribution was subsequently studied by Fowler and Perkins[4] in a systematic way. This distribution has been theoretically derived by Barkas,[5] who finds that the gap-length coefficient is to be identified with the true grain density in emulsion. In bubble chambers, the same distribution has been observed by us and previously by Willis et al.[6] and Blinov et al.,[7] namely

$$N(\ell) = N(0)\exp(-g\ell), \tag{1}$$

where $N(\ell)$ is the number of gaps exceeding length ℓ and g is a constant depending on the velocity β of the particle.

From this distribution, the average separation between the "true bubbles"--that is between the "thermal spikes"--is $\bar{l} = 1/g$, which means that g is equal to the number of "true bubbles" per unit length. We can write the number of gaps between two successive "thermal spikes" exceeding length l per unit length as

$$n(l) = g \exp(-gl). \tag{2}$$

Now, assuming that the distance between two successive "thermal spikes" has to be greater than a in order to resolve gap lengths greater than zero measured between the successive edges of "bubbles," one has the gap density, G, or the blob density, B, as defined before,

$$B = G = g \exp(-ga). \tag{3}$$

All the above formulae have been theoretically treated by Barkas[5] for emulsion.

III. Experimental Results

A. General

We have measured track density in the 30-inch Powell propane chamber and the 15-inch Alvarez hydrogen bubble chamber of the Lawrence Radiation Laboratory. All measurements have been made on the film under microscopes using magnification of 100 to 200. Pictures usually taken for the investigation of the physical problems have rather high bubble density to facilitate observation on the projection table. Hence at the ends of their ranges the number of gaps is too small to make any practical measurement. For this and for the other reasons to be mentioned, high statistical accuracy could not be obtained in the case of hydrogen bubble chamber; extensive measurements have been feasible in the case of the propane chamber, and we shall therefore report on these data in detail and briefly mention the results with the hydrogen bubble chamber.

B. Propane Bubble Chamber

With the kind cooperation of Dr. Wilson Powell and his group, a special run of the chamber exposed to a proton beam of the Bevatron was possible under special operating conditions. The chamber was underexpanded to reduce considerably the bubble size as well as bubble density, and a parallel beam of protons was selected to stop in the chamber; the operating conditions were kept uniform as far as possible.

Some data on the proton beam are shown in Figs. 1 and 2; the fractional-height distribution of the tracks at the entrance end of the chamber is shown solid in Fig. 1 and that at the stopping end dotted. The beam at entrance is quite peaked at a region slightly higher than the middle point of the chamber (from the bottom); the end points of the tracks, however, show a wider spread, as is expected from Coulomb scattering. The change in depth between the entrance and the stopping ends for the same sample of tracks is shown in Fig. 2. These distributions would be used in estimating the correction factor in the measurements for the dip of the tracks and for the variation of the ionization with the depth of the chamber.

The gap lengths have been measured on the films with a microscope under 100 X magnification. Two sets of measurements have been made (each set included about 100 tracks)--one with the help of an eyepiece with calibrated scale and the other with the help of a filar micrometer; in the latter case a line moved along the eyepiece scale and the gap length could be read more accurately from a micrometer scale fitted to the eyepiece. In fact, we did not need to measure the gaps accurately. It was sufficient to know to which interval in the differential distribution the gap belonged. The data have been combined to plot the integral distribution. The bubble images are not sharply defined, and this introduces some subjectivity in the measurements. The boundary of the image is defined to where the light intensity first matches the background of the film; we found that the measurements following this convention can be reproduced and do not appreciably vary with different observers.

For the high-velocity interval (at which $\beta = v/c$ is large), the number of counts per track is reasonably large (about 300), so that g can be evaluated for each track with statistical significance; the individual values of g agree within the statistical errors. This indicates that the chamber was working under reasonably uniform operating conditions during the run and that the pictures used for the measurements are of the same quality. Consequently, the combined data from all tracks can readily be used for evaluating g with higher statistical accuracy.

Counts from about 20 tracks in the high-β and about 200 in the low-β intervals have been obtained to determine g. A typical distribution of gap lengths over a velocity interval for proton tracks in this chamber is shown in Fig. 3. The distribution is found, within our statistical accuracy, to be exponential over all ranges of the tracks we have measured, both in propane and in hydrogen bubble chambers.

To determine g, a least-squares fit to the semilog plot of $N(\ell)$ versus ℓ was obtained by using a suitable IBM 650 program. The program fits the

points to a straight line, giving proper weights to the corresponding points, and calculates the slope of the curve and its associated statistical error.

We report the values of g simply as obtained for the high-β interval, and introduce corrections to those at low velocities. The following correction factors to be used at the stopping end of the track compared to that at the entrance (correction factor = 1) can be readily evaluated:

1. Correction for foreshortening of the tracks due to distortion.

Measurements on the fiducial marks on the chamber reveal that, for a horizontal track, g at the stopping end has to be multiplied by a factor 0.986.

2. Correction due to depth variation.

Willis et al.[6] report strong temperature dependence of g (about 50% change in g per $^{\circ}$C). However, other causes, such as hydrodynamical conditions and the optical system, may introduce some effects also.

To investigate this, we have measured the gap distribution of fast steep tracks passing through the chamber and also of the proton tracks entering at different depths in the chamber. The variation of g with depth is found to be quite small; in individual measurements, the values of g at the bottom and at the top agree within the statistical errors. From the over-all measurements we may say that the fractional change in g, $\Delta g/g$, over the whole height of the chamber is no more than 20%. As mentioned before, we normalize our measurements to those of the proton beam at entrance, and therefore the variation of height at the stopping end with respect to its height at the entrance is relevant in the estimate of the correction factor. From Fig. 2 the average value of Δh is $\overline{\Delta h} = -0.011 \pm 0.002$, where Δh is expressed as fractional height (total height = 1); over this depth $\Delta g/g$ would vary at most by $\pm$ 0.2%. This small variation can therefore be neglected.

During the operation of the chamber, no device for measuring the temperature gradient was used; it is believed, however, that this should not

exceed 0.5°C. Comparison of our data on $\Delta g/g$ with those of Willis et al.[6] indicates that the temperature gradient over the height of the chamber (6 inches) was less than 0.5°C.

3. Correction for dip angle.

This can be readily made from the mean value of $|\Delta h|$, and the average correction factor is 0.985.

The correction factor when combined is then 0.97 at the end of the track, compared to unity at the entrance point, and would lie between these limits for the intermediate parts of the track.

The variation of g with velocity β thus evaluated is shown in Fig. 4. The lengths hereafter refer to the actual dimension in the chamber. The values of β have been obtained from the range-energy relation, and the average value of β over the interval of measurement has been calculated, with proper weight given to each value of β according the energy loss at that point. A least-squares fit of the points to a straight line gives $g = g_0 \beta^{-n}$, where $g_0 = 5.92 \pm 0.33$ cm, $n = 1.71 \pm 0.11$. The errors correspond to statistical accuracy.

It is of interest how the gap density G varies with the track density g. In Fig. 5 we present the number of gaps per unit length (only gaps greater than 0.1 mm have been counted to ensure objectivity) versus the experimentally determined values of g. According to Eq. (3), G should have a maximum at a g value given by

$$g = 1/(a + \epsilon). \tag{4}$$

G indeed passes through a maximum; the position of the maximum may be used to determine the value of a. With $\epsilon = 0.1$ mm, we obtain $a \approx 0.31$ mm, which agrees very well with the measured average bubble diameter $\bar{D} = 0.305 \pm 0.030$ mm; a should, indeed, be identified with the average bubble diameter, as has been shown by Barkas[5] for emulsion.

Though there seems to be qualitative agreement between Eq. (3) and the plot in Fig. 5, the experimental data indicate some complexity. For

example, the curve shown in Fig. 5 as calculated from Eq. (3) by using the value of a from the position of the maximum in G gives a poor fit to the data. The fit can obviously be obtained by varying a with g; in Fig. 6, we show the behavior of a with g which would satisfy the relation (3).

The optical system of the chamber might impair the resolution of measurement in a complex fashion in different parts of a track and also from track to track, this may be a reason for the variation of a with g. However, direct determination of bubble diameter along the track length did not reveal such a drastic variation.

C. Hydrogen Bubble Chamber

The original idea was to measure the ionization of protons and pions originating from the decay of Λs produced by K^- capture in the chamber. In this way, a direct comparison of track density of protons and pions is possible, since they have the same age. However, the protons from the decays were found to be too slow to give gap distribution of statistical significance; only the measurements on the pions are reported in this case. The tracks had to satisfy the following criteria:

(i) dip angle $\leq 10^\circ$ deg,

(ii) depth of the point of Λ decay approximately halfway between the top and the bottom of the chamber.

Since the events were distributed over a large number of photographs, for consistency of measurement the fast beam tracks were used for calibration.

Here the measurements have been done in the same way as before, but under 210 X magnification. The variation of g with β for pions and a few electrons is shown in Fig. 7. The momentum of the particles is determined from the kinematics of the decay of Λ.

The statistical accuracy is rather poor in this case owing to the small number of measurable events. A least-squares fit to the data to a relation $g = g_0\beta^{-n}$ yields $g_0 = 24.4 \pm 5.9$/cm, $n = 1.86 \pm 0.37$. No detailed analysis of

the data, as in the case of the propane chamber, is possible. Kenney[8] in a recent investigation, in a hydrogen bubble chamber, has observed the same β dependence of g as ours.

IV. Discussion

The mechanism of bubble nucleation is not yet well understood. Bugg has discussed the problem in a recent review article.[9] If the energy is imparted to the bubbles by the stopping delta rays, then the track density g should be well represented by a $1/\beta^2$ dependence; the number of δ rays per unit length produced by a heavy particle colliding with electrons at rest (hard-collision approximation) between the limits of energy E_1 and E_2, which is assumed to lead to bubble formation, is

$$n = \frac{k}{\beta^2}\left[\frac{1}{E_1} - \frac{1}{E_2}\right] ; \quad k = 37.13 \text{ kev/cm.} \tag{5}$$

The collision cross section involves some other terms which can be neglected for all β. This mechanism would not lead to a relativistic rise in the track density.

Another mechanism of bubble formation would be the "storage" of energy from the energy loss of the passing particle; if an amount of energy exceeding Δ is to be stored in a dimension x for the nucleation process, then the β dependence of g would be somewhat different from the δ-ray mechanism. It has been pointed out to us by Dr. Walter H. Barkas that Landau's treatment of ionization loss may be appropriate in this case. We have

$$g = 1/x\, \psi\left(\frac{\Delta-\Delta_0}{\xi}\right), \tag{6}$$

where ψ is the universal function given by Landau;[10] and

$$\Delta_0 = \xi\left(\ln\left(\frac{2mc^2}{I^2}\ \xi\,\gamma^2\beta^2\right) - \beta^2 + 0.37\right),$$

$$\xi = x\ \frac{2\pi N e^4 \rho}{mc^2\beta^2}\ \frac{\Sigma Z}{\Sigma A} = \frac{kx}{\beta^2} ; \quad k = 37.13 \text{ kev/cm.}$$

I is the ionization potential, 50 ev in propane.

In our case of an underexpanded chamber, $(\Delta-\Delta_0/\xi$ is quite large, and $\psi(\eta)$ can be represented by $1/\eta$, as shown by Landau. Then Eq. (6) can be written as

$$\frac{1}{g} = \frac{\beta^2\Delta}{37.13} - x\,\ell n\,x - 16.91\,x \tag{7}$$

$$= \beta^2\Delta' - a, \quad \Delta' = \frac{\Delta}{37.13}, \quad a = x\,\ell n\,x + 16.91\,x.$$

In the numerical values put into the equations, energy has been expressed in kev and length in cm. We note that β dependence of g in this case would not necessarily follow $1/\beta^2$ law.

For the purpose of comparison with experimental results, few systematic measurements are available. Consistent methods similar to ours have been used by Blinov et al.[7] for track-density evaluation. Expressing g as $g = g_0\beta^{-n}$, they obtain $n = 2.07 \pm 0.17$, which is consistent with the δ-ray mechanism. However, they observe a relativistic rise of g for fast electrons—contrary to the δ-ray formation mechanism due to hard collisions. Our value of $n = 1.71 \pm 0.11$ seems to be somewhat less than 2. We also find that g is practically a linear function of relative ionization loss I_{rel}. Assuming the range-energy relation to be essentially correct, we can evaluate the relative ionization $I_{rel} = I_\beta/I_\beta = 0.5$ from the equation

$$I_\beta = (dE/dX)_\beta = \frac{k}{\beta^2}\left[\ell n\left(\frac{2mc^2}{I}\beta^2\gamma^2\right) - \beta^2\right]. \tag{8}$$

Our plot of g versus I_{rel} for the propane chamber is shown in Fig. 8; a straight-line fit to the data is quite good. We note in this connection Glaser et al.[2] have reported that the bubble density is not a linear function I_{rel}. However, their method of evaluating bubble density is the conventional bubble counting, with greater possibility of loss of bubbles with the increase of the density.

On the basis of Landau's treatment, our data gave $\Delta \approx 8$ kev and $\alpha = -0.0026 \pm 0.00245$; this value of α gives the β dependence as observed in our case, but x has no physical solution.

Over the β interval 0.1 to 0.9, the β dependence of dE/dX can be well approximated by a β^{-n} law, with $n = 1.68$. Our value of n as obtained from the experimental data is in good agreement with this; also the relativistic rise observed by Blinov et al. would favor the assumption that g is proportional to dE/dX. However, if this is really the case, it would be difficult to visualize bubble-nucleation mechanism as a simple process, such as immediate generation of a "thermal spike" by a single δ ray, or by storage over its dimension of energy exceeding a certain amount

V. Conclusions

Our investigation shows that the gap-length distribution for a given β is exponential within our statistical accuracy over the entire range of the measurements. The mean gap length determined from this distribution gives a measure of the ionization of the particle. For practical purposes, we feel this method to be the least subjective one. Another advantage of this technique is that it can consistently be used over a wide range of velocities, provided sufficient counts are obtained with well-defined objective criteria. In bubble counts, the subjectivity of the observer would affect the consistency of measurement, particularly for heavy tracks; an attempt to determine the number of "bubbles" in a blob is difficult and somewhat unreliable, more so for dense tracks.

We find that g, the track density dependence on β, is well represented by $g = g_0 \beta^{-n}$, where n is very near to 2. The blob or gap density seems to be related to g in the same way as in emulsion, namely

$$\begin{matrix} B(\epsilon) \\ G(\epsilon) \end{matrix} = g \exp[-g(a + \epsilon)].$$

As required by this relation, G indeed passes through a maximum with the variation of g, and the position of this maximum determines a value of a which is in excellent agreement with the average diameter of the bubbles. However, in our case the above relation would hold if a were varied with g. B or G would be as sensitive a function of β as g if ga were very small; for low values of β, ga tends to be appreciable and B and G become less sensitive functions of β. Therefore for particle identification, g would be more advantageous.

We may remark that the method of evaluating g is not too slow and time-consuming a process, as may be thought. Even without having some highly mechanized system for channeling the distribution of gaps, the method may compete with the straightforward bubble counting. In a

momentum-analyzed beam, if the βs of different particles are reasonably separated, a fast evaluation of g can be made to estimate the proportion of different particles. In this situation, the data on gap distribution need not be recorded in as many intervals as we have done; with a mechanical counter assembly having three or four push buttons to register three or four groups of gaps within rather long intervals, one can register the distribution by pressing appropriate keys. If the tracks are aligned along a certain axis of the microscope stage, one hand can be used to pass the track under the eyepiece rather rapidly and the other for pressing the buttons while the observer is looking through the microscope. Then a plot of the observed values of $N(\ell)$ versus ℓ may be made on semilog paper and the slope of the straight line visually fitted would determine g; with reasonable number of counts (more than 100), we find that the visual fit is quite good as compared to a least squares fit. In this way, the speed and the reliability in the evaluation of g are found to be quite satisfactory.

Acknowledgments

We are indebted to Dr. Wilson M. Powell and his group for the trouble of running the propane bubble chamber under special conditions for our purpose, and for many helpful suggestions. We are thankful to the hydrogen chamber group for allowing us to make measurements on their films and furnishing us with the kinematical data of the events. This work was initiated with the suggestion of Dr. Walter H. Barkas, who contributed significantly to many discussions and criticism. We also had the privilege of having profitable help from a number of individuals of our group in some phases of the work.

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Figure Legends

Fig. 1. Height distribution of proton tracks in propane chamber at the entrance end (solid) and the stopping end (dotted); the heights are expressed in fractional units, assuming the total height from bottom to top (6 inches) to be unity.

Fig. 2. Distribution of the variation of height, Δh, between the points of entrance and stopping of the tracks. Δh is in fractional units, positive for a track moving towards the top of the chamber and negative in the reverse direction.

Fig. 3. Integral distribution of gaps exceeding a length ℓ versus ℓ; the lengths shown are in scale divisions of the eyepiece vernier as measured on the film; one scale division corresponds to 7.18 μ in the chamber.

Fig. 4. Track-density dependence on the velocity β in propane chamber; the lengths refer to chamber dimensions. The solid line corresponds to the least-squares fit of experimental data with slope $n = 1.71 \pm 0.11$. Plot of normalized dE/dX versus β has a slope $n = 1.68$ and almost coincides with this line. For comparison, $1/\beta^2$ dependence of g normalized at $\beta = 0.5$ is shown dotted.

Fig. 5. Density of gaps larger than 0.1 mm versus the track density g in propane. The curve corresponds to $G = g \exp[-g(a + 0.1)]$, $a = 0.31$ mm.

Fig. 6. Variation of a with g in propane, if G follows the expected g dependence.

Fig. 7. Dependence of track density g in hydrogen chamber on β; the lengths here also refer to the original dimensions of the chamber.

Fig. 8. Dependence of track density g in propane chamber on the relative energy loss I_{rel} of protons.

78

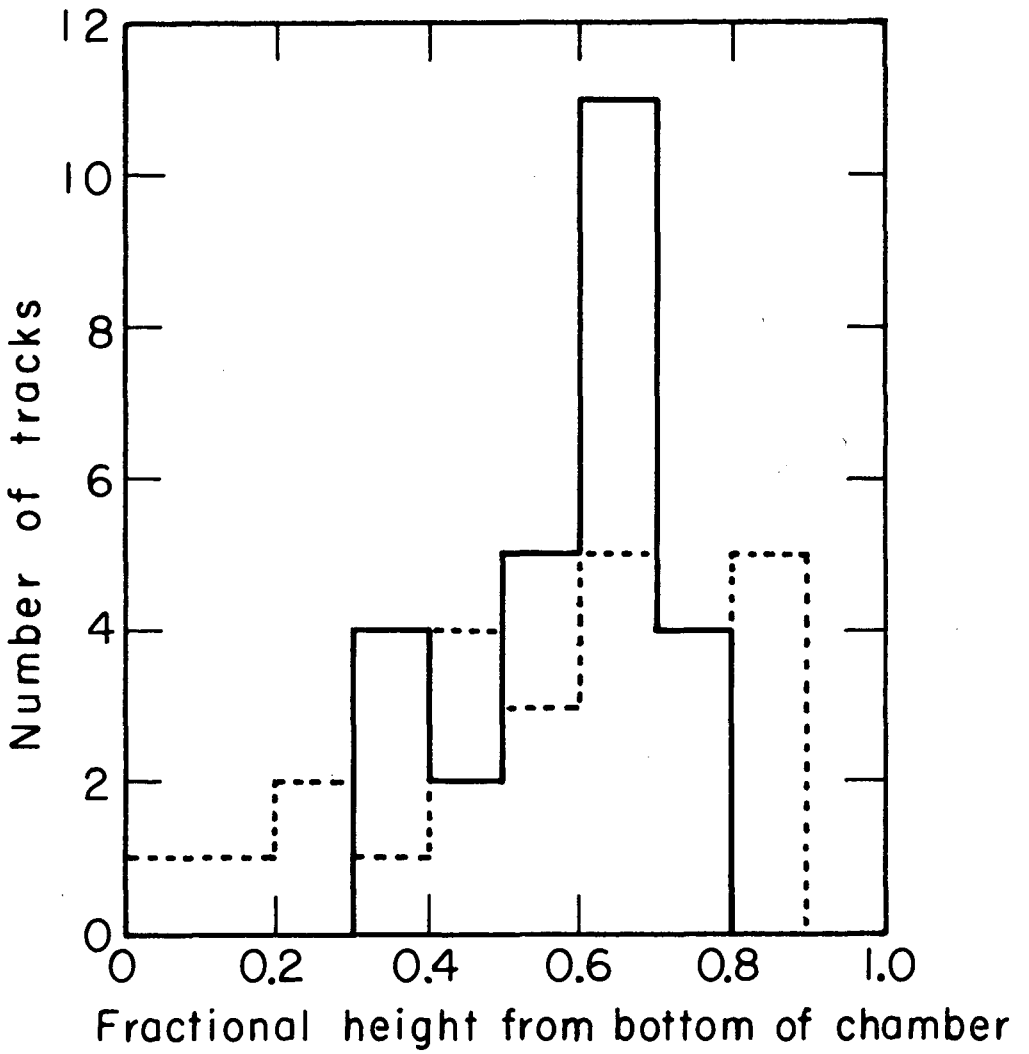


Fig. 1

58360-1

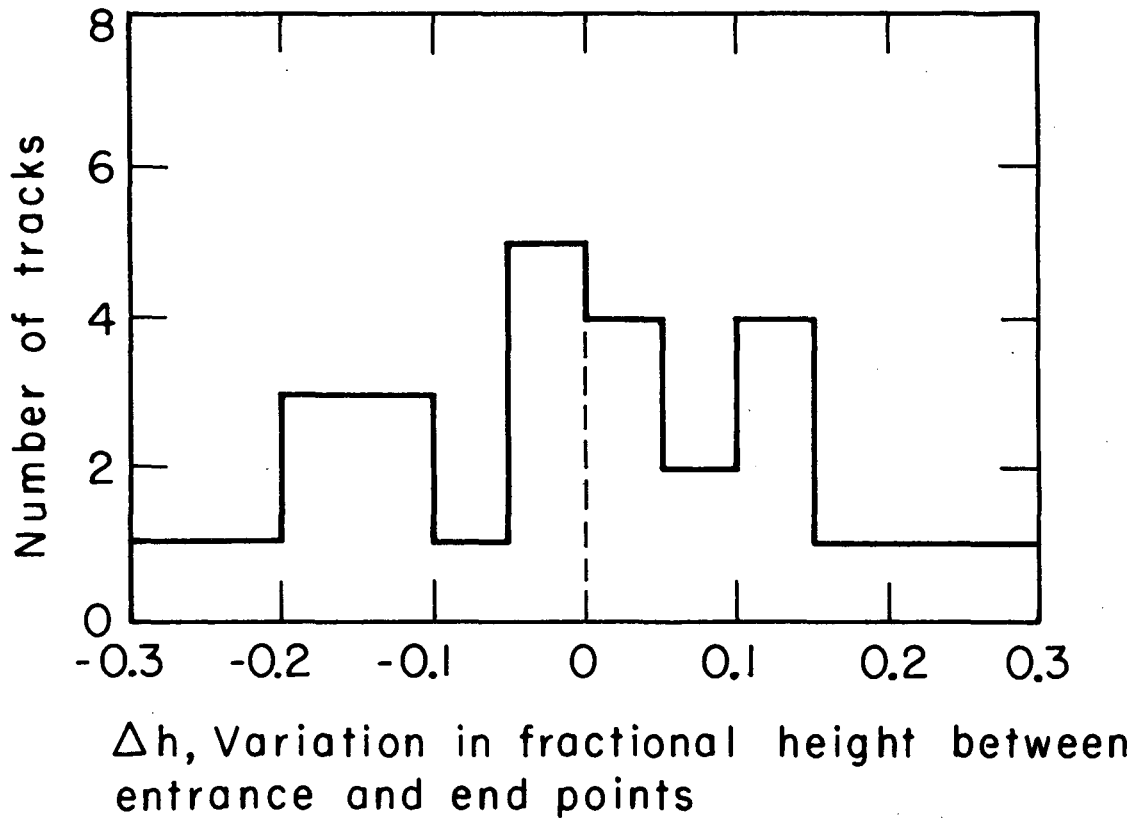
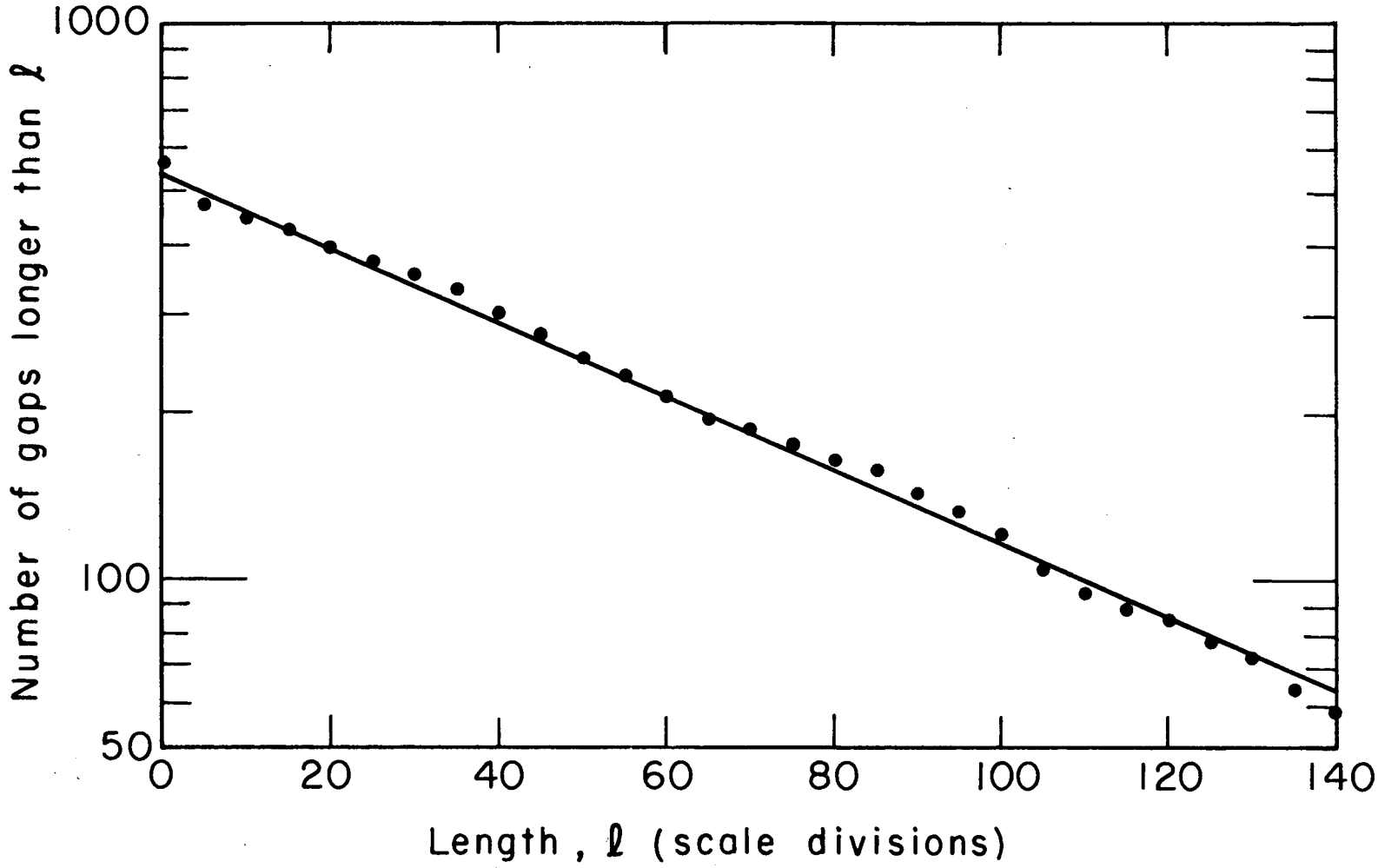

Number of tracks
0
2
4
6
8
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Δh, Variation in fractional height between entrance and end points

Fig. 2


1000
100
50
Number of gaps longer than ℓ
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20
40
60
80
100
120
140
Length , ℓ (scale divisions)

Fig. 3

58362-1

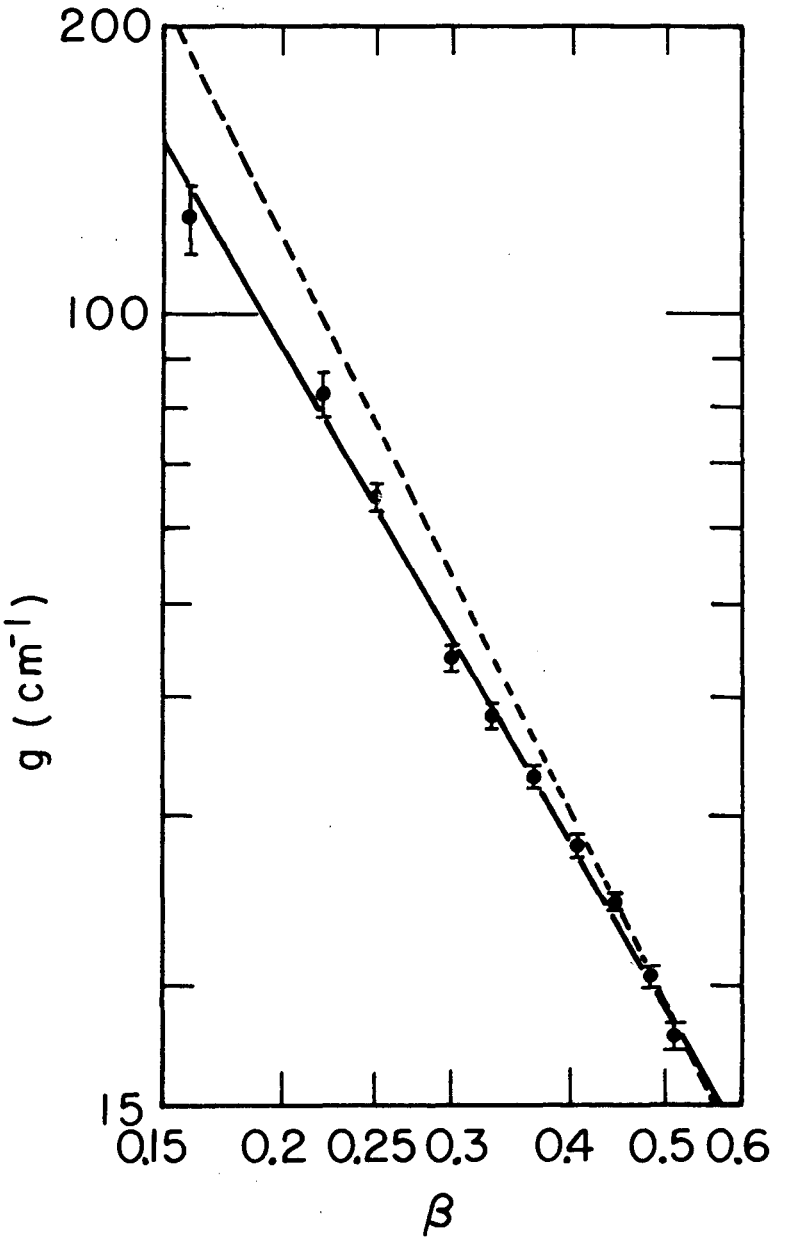

Fig 4

58363-1

6B364-1

66

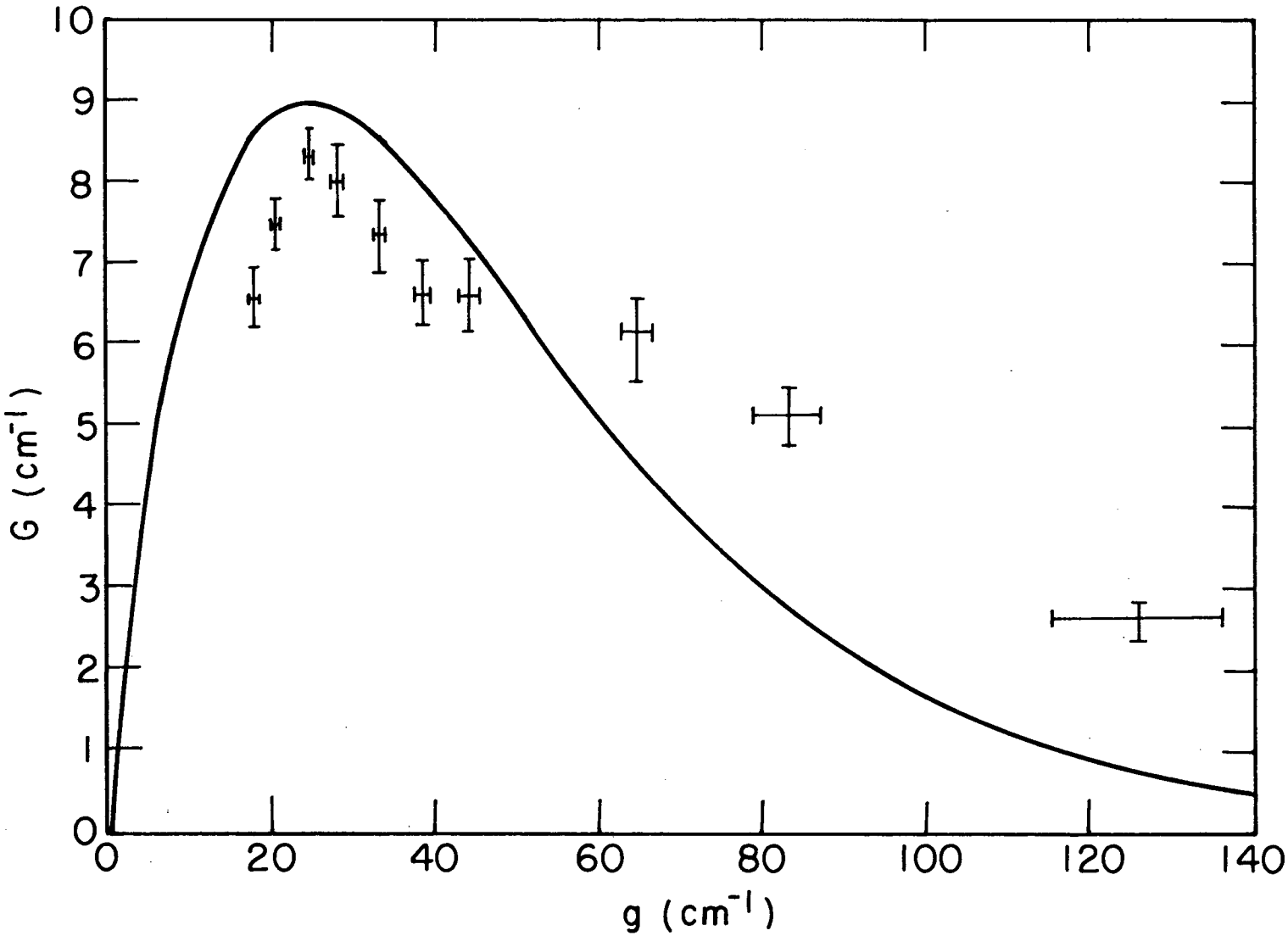

Fig. 5

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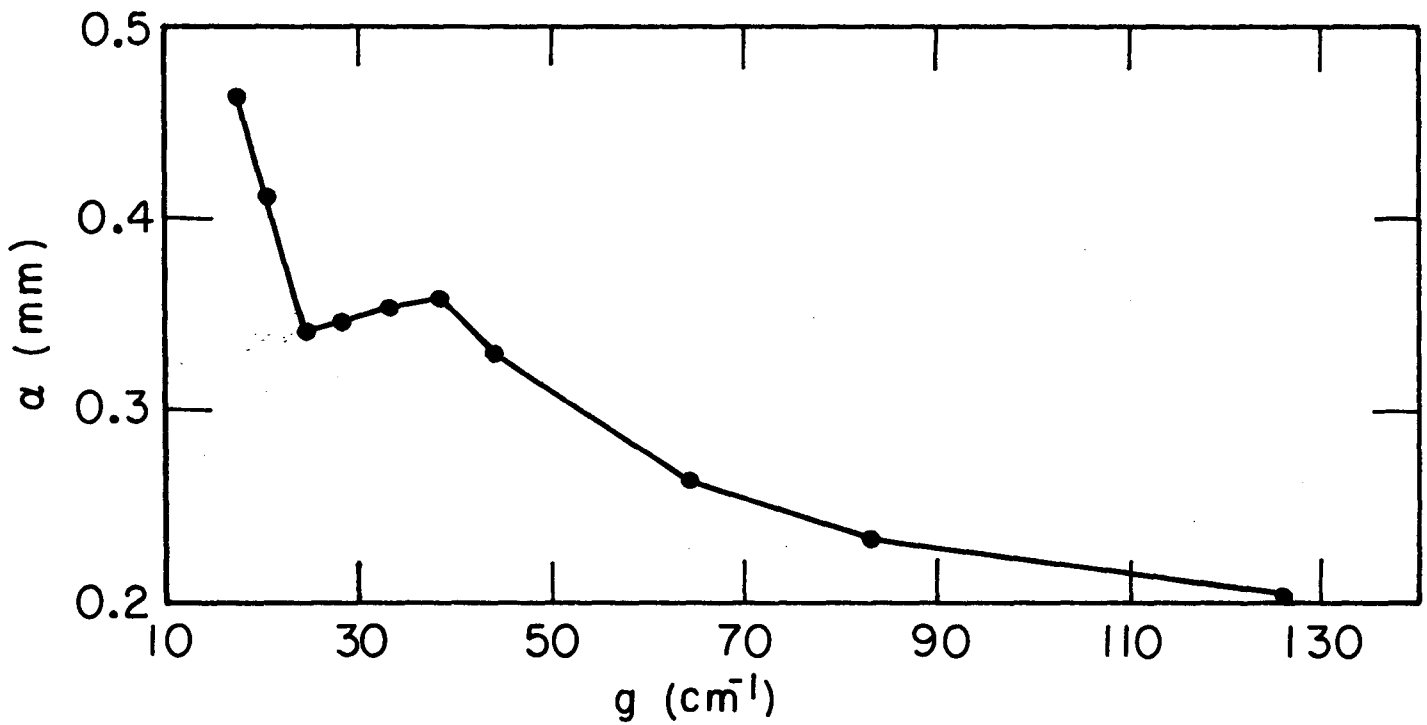

Fig. 6

58365-1

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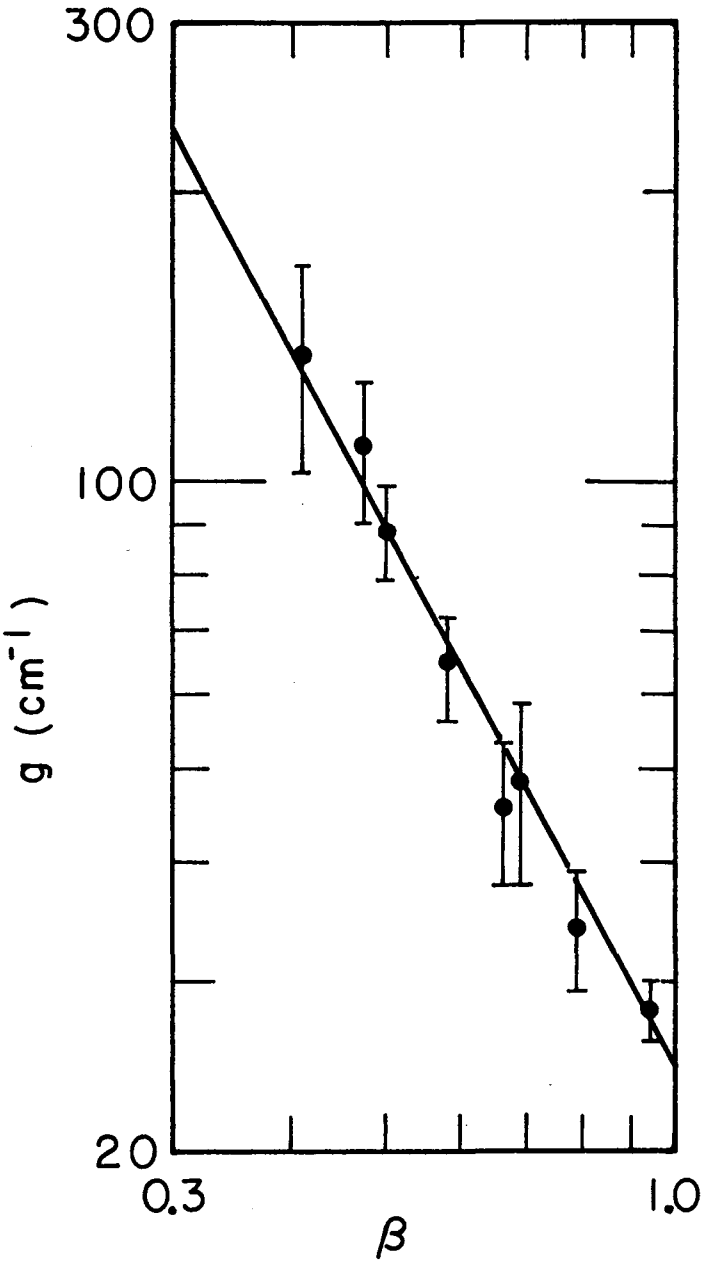

Fig. 7

58366-1