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ON THE WIDTH OF HEAVY ION TRACKS IN NUCLEAR EMULSIONS - A STUDY OF THE ENERGY DOSE CONCEPT FOR ION VELOCITIES $\beta \leq 0.3$.

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CONTENTS

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Abstract.

Light absorption profiles of tracks of heavy ions have been recorded using a nuclear track photometer with a narrow slit. The tracks were produced by heavy, stopping, cosmic ray particles with the charges in the interval $6 \leq Z \leq 26$. Measurements were made in both Ilford G5 and Ilford K2 nuclear emulsions. The experimental data is compared with the theoretical distribution of energy dose around the path of a passing ion. The dosage has been calculated using the formalism of the track formation theory developed by Katz and coworkers. Fairly good agreement between experiment and theory is established for the measurements in Ilford K2 emulsion. For the measurements in Ilford G5 there are indications of some disagreement between experimental and theoretical widths.

I. Introduction.

Different theories of the formation of heavy ion tracks in nuclear emulsions have been proposed. Lonchamp (1) based his theory on the effect of the secondary electrons (δ rays) and assumed that the track edge would be observed as opaque only when the number of δ rays per unit length exceeded a certain value. The simplified theory of Lonchamp was, however, not consistent with the experimental findings of Bizzeti and Della Corte (2), who proposed a track formation model based on an energy flux criterion. A modification of this model was presented by Katz and Butts (3), who introduced the concept of critical energy dosage. This theory has been further developed by Kobetich and Katz (4) and by Katz and Kobetich (5).

In order to discuss the relevance of the different theories of track formation there is need for a detailed experimental study of the width of heavy ion tracks in emulsion and its dependence on the particle charge and velocity. Also the dependence of the width on the detector sensitivity may give useful information about the track formation mechanism.

In this report we will present results from an experimental test of the track formation theory by Katz and coworkers. Track widths of heavy ions in nuclear emulsions have been determined by measuring light absorption profiles of the tracks using a photometer with a narrow slit moving perpendicularly across the track. The tracks are produced by primary cosmic ray particles with the nuclear charges in the interval $6 \leq Z \leq 26$. Two types of emulsion with different sensitivities have been investigated. The experimental track widths are compared with calculations of the spatial distribution of the ionization energy delivered by a heavy ion passing through a medium.

II. Experimental details and measurements.

The track width measurements have been made using a nuclear track photometer, described by Håkansson et al. (6). The photometer is shown in Fig. 1. The basic unit of the photometer is a Leitz microscope, whose eyepiece has been replaced by an optical system with a narrow slit and a photomultiplier. The slit has the dimensions 4.8 x 0.066 mm^2, corresponding to 11.4 x 0.16 μm^2 in the emulsion plane when a 100 x objective is used. The track segment to be measured is adjusted parallel to the slit. A revolving mirror system moves the image of the track segment across the slit. The variations in light intensity during this motion is registered as an absorption profile by a pen recorder.

We have made width measurements of tracks in two nuclear emulsion stacks, one consisting of Ilford G5 and the other of Ilford K2 emulsion plates. The stacks were exposed to the primary cosmic radiation in balloon flights from Fort Churchill. In our experiment we have selected about 40 flat tracks produced by particles with the nuclear charges Z = 6, 12, 18, 24 and 26, which stopped in the emulsion. The mean dip angle of the tracks in the developed emulsion was 4^o. The charges of the particles had been determined by photometric measurements in earlier investigations (7-9). In these works the mean value of the charge resolution was about 0.3 units of charge.

A profile was registered for each track at every 10 microns in the residual range intervals 10-120, 180-220, ... 980-1020 μm. Figs. 2a and 2b show some examples of such profiles. For every profile a base line was drawn representing the light background in the emulsion pellicle. We have measured the width of the profiles at some chosen levels above the base line. These levels correspond to different degree of light absorption.

III. Comparison with theory.

Using the formalism presented by Katz and Kobetich (5) we have computed the distribution of energy dosage, E(t), as a function of the distance, t, from the path of a moving ion. From the point distribution E(t), the mean energy dose $\bar{E}(t)$, averaged over a volume representing an undeveloped emulsion grain, has been calculated, following ref. 5. In Fig. 3 we show the average dose distribution

$\bar{E}(t)$, calculated for Ilford K2 emulsion, with the radius of the sensitive sphere $a_o = 0.13$ µm.

According to Katz the probability, P, for the development of an emulsion grain is a function of the mean dose $\bar{E}$ of ionization energy to which the grain is exposed. The assumed relation is given by the expression

$$P(t) = 1 - e^{-\bar{E}(t)/E_o}$$

where E_o is the "characteristic" dose at which 63% of the exposed grains are rendered developable. We determined E_o for our emulsion stacks by grain counting the tracks of lightly ionizing particles (5). For the Ilford G5 emulsion the value was found to be $E_o = 4 \cdot 10^4$ ergs/cm^3 and for the Ilford K2 emulsion $E_o = 6 \cdot 10^5$ ergs/cm^3. The characteristic dose depends, of course, on the sensitivity and on the processing conditions of the emulsion.

Theoretical track widths have been calculated from the assumed probability distribution P(t). The theoretical width of a track segment is given by the extension of the region, where the probability, P(t), exceeds a predetermined value. When the theoretical width is compared with the measured track width, P(t) has been adjusted to give the best agreement. For the Ilford K2 emulsion, where a track has a well defined core boundary we simply consider the light absorption as a function of P(t), i.e. the number of developed grains in the object plane. In the sensitive Ilford G5 emulsion, the track core is surrounded by a large number of δ rays. The more or less defocused grains contribute to the light absorption. Accordingly the light absorption must be considered as a function of the developed grains within a volume. The theoretical width of a track segment has in this case been calculated from

$$F(t) = \int_{-Z}^{+Z} P(x)\, dz$$

where $x^2 = t^2 + z^2$, and F(t) is a parameter, which is constant for a given light absorption. The integration of the probability accounts for all the developed grains within a depth interval $\pm Z$, enclosing the track. This method of calculation implies that the photometer works with a beam of parallel light. This is not quite true, though experiments have shown that the measured track widths do not depend on the shape of the light cone to any great degree.

During the development of the emulsion, the sensitized crystals will grow, and the diameter of a developed grain will, on the average, increase by a certain amount, depending on the type of emulsion and on the conditions of processing. As pointed out by Bizzeti et al. (10), the effect of the development on the track width can be accounted for by an additive term, λ_0. The numerical value of λ_0 has been determined from our experimental data and has been added to the theoretical widths before the comparison with the experimental track widths.

For the measurements in the Ilford K2 emulsion we have used the profile width at half the profile height. These track width values for different charges are seen in Fig. 4a together with theoretical track width curves. The theoretical curves have been calculated for P(t) = 0.13 and with λ_o = 0.4 μm. As can be seen from the graph the measured track widths are quite well described by the theory. The agreement covers the charge interval $6 \leq Z \leq 26$ and the residual range interval $100 \leq R \leq 1000$ μm.

For the Ilford G5 emulsion, the theoretical track widths, calculated with different values of the track parameters could not be put in good accordance with the track widths at half the profile height. We found, however, a somewhat better agreement when we studied only the track core and used the profile width at 5/6 of the height. The comparison between experimental and theoretical track widths is seen in Fig. 4b. The parameter values are P(t) = 0.7 and λ_o = 0.3 μm. For charges $Z \leq 12$ there is a generally good agreement in the whole range interval, though for higher charges and in the last 300-500 μm it is not possible to explain the experimental track width from the assumptions made in the theory.

We wish to express our sincere gratitude to Prof. K. Kristiansson for much advice and valuable discussions.

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Figure captions

Fig. 1. A schematic diagram of the optical part of the photometer.

Fig. 2a-b. Examples of track profiles of an iron nucleus at different residual ranges.

a) Ilford K2 emulsion

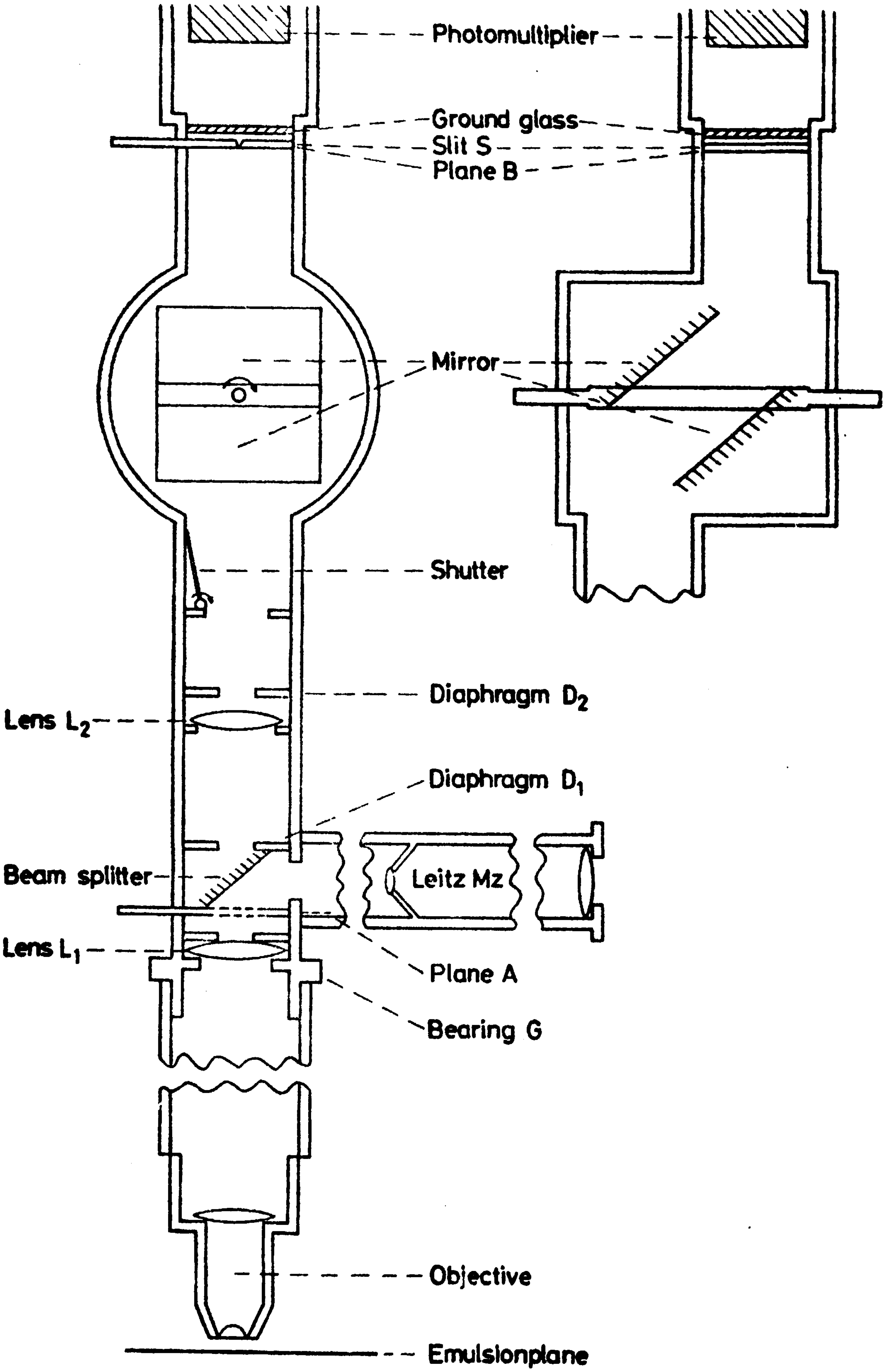
b) Ilford G5 emulsion

Fig. 3. Distribution of the mean energy dose plotted against the distance, t, from the ion's path.

Fig. 4a-b. Experimental track widths plotted against range together with theoretical curves.

a) Ilford K2 emulsion

b) Ilford G5 emulsion.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Ground glass
Slit S
Plane B
Mirror
Shutter
Diaphragm D_2
Lens L_2
Diaphragm D_1
Beam splitter
Leitz Mz
Lens L_1
Plane A
Bearing G
Objective
Emulsionplane

Fig. 1

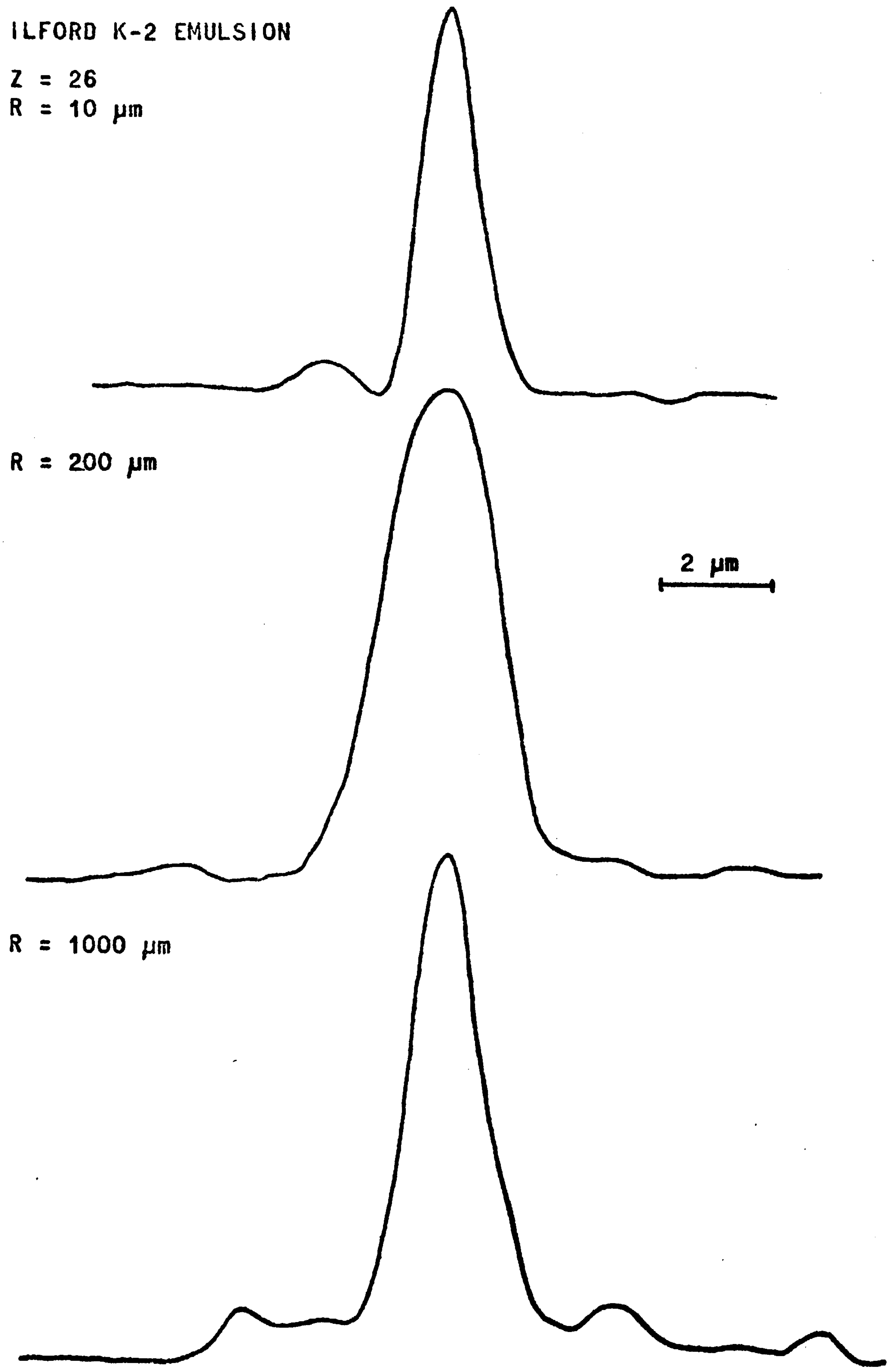

Fig. 2a

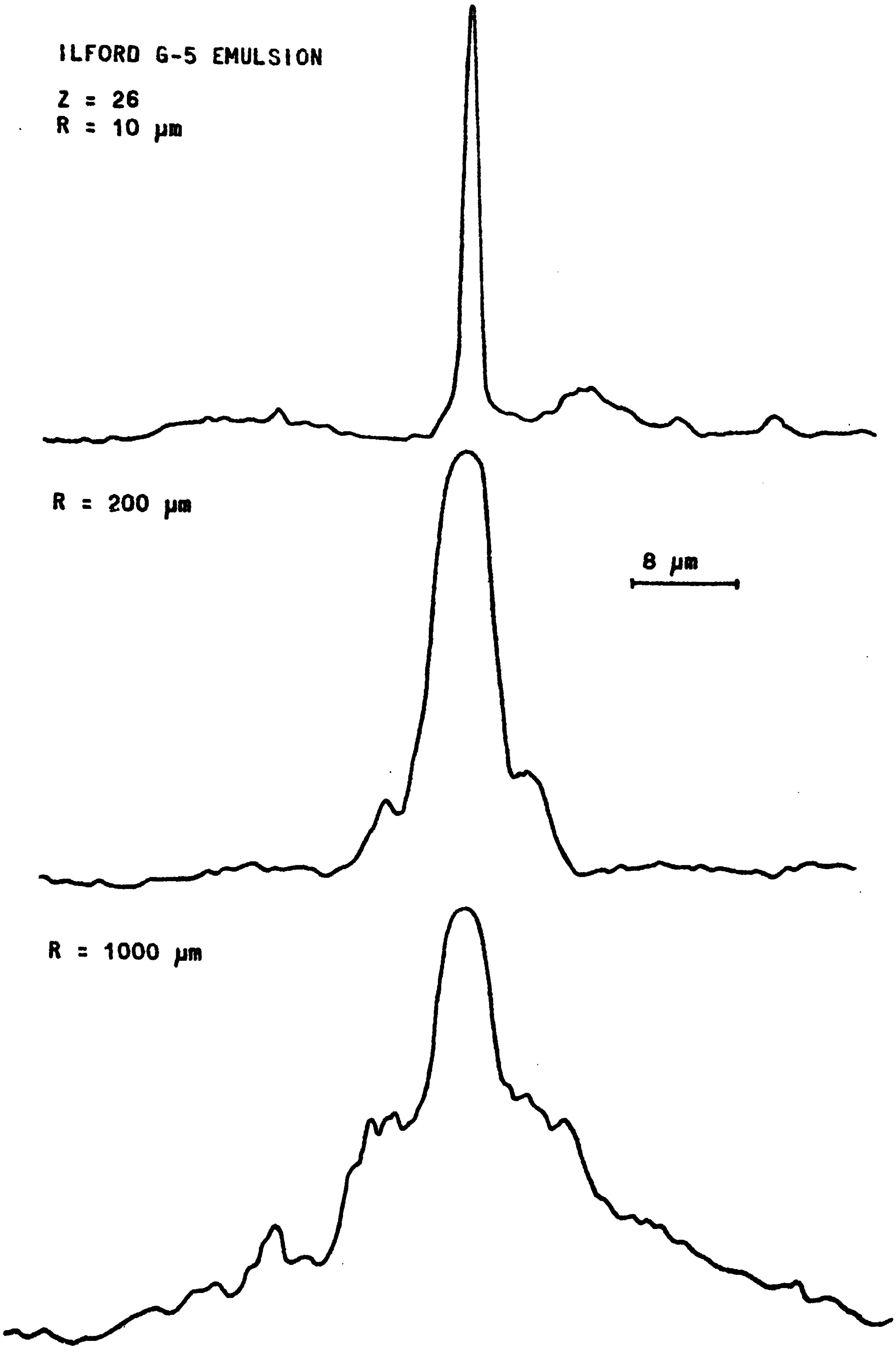

Fig. 2b

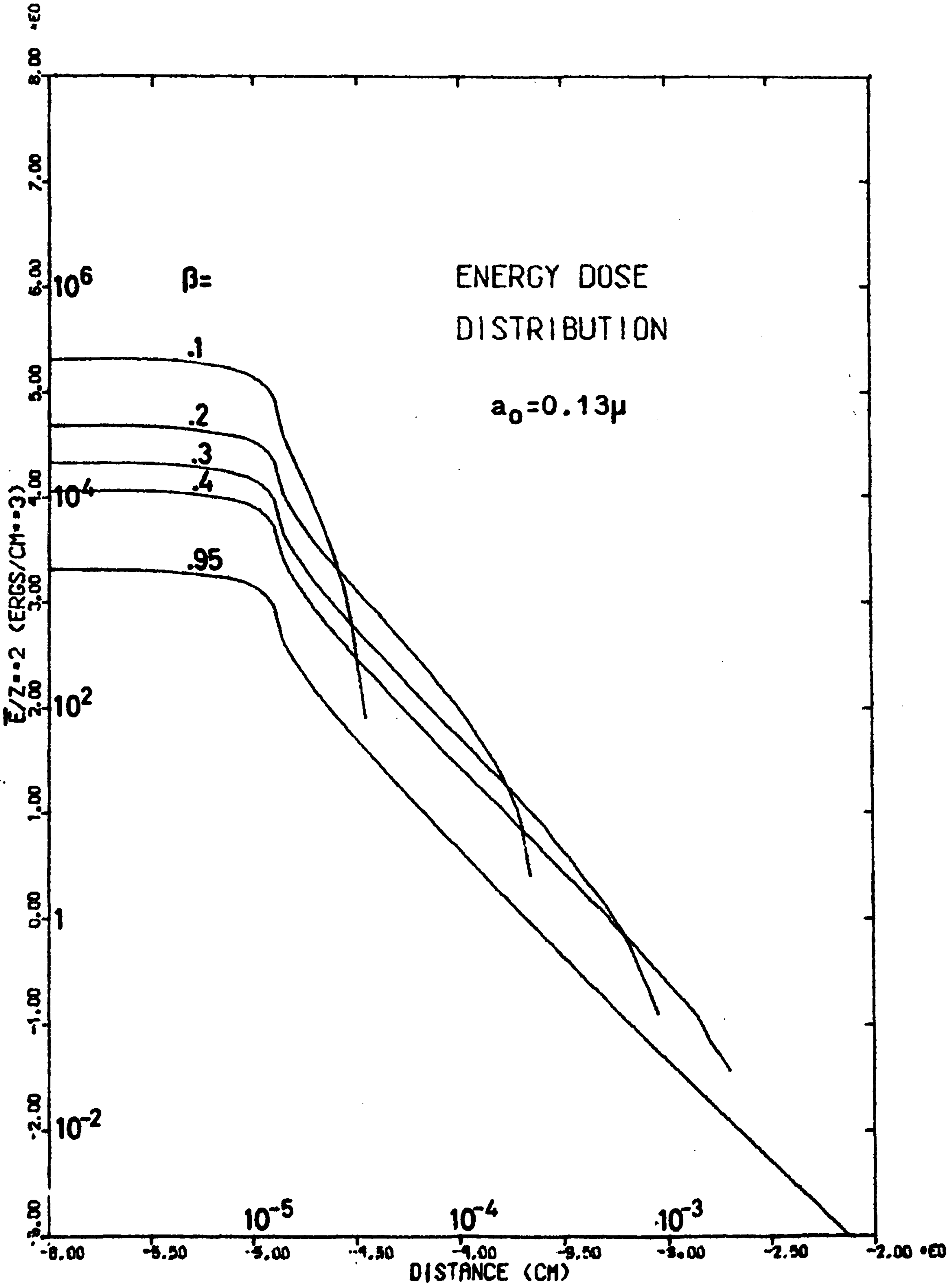
ENERGY DOSE DISTRIBUTION
a_0=0.13μ
β=
.1
.2
.3
.4
.95
10^6
10^4
10^2
1
10^{-2}
10^{-5}
10^{-4}
10^{-3}
E/Z**2 (ERGS/CM**3)
DISTANCE (CM)
8.00 *E0
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-6.00
-5.50
-5.00
-4.50
-4.00
-3.50
-3.00
-2.50
-2.00 *E0

Fig. 3

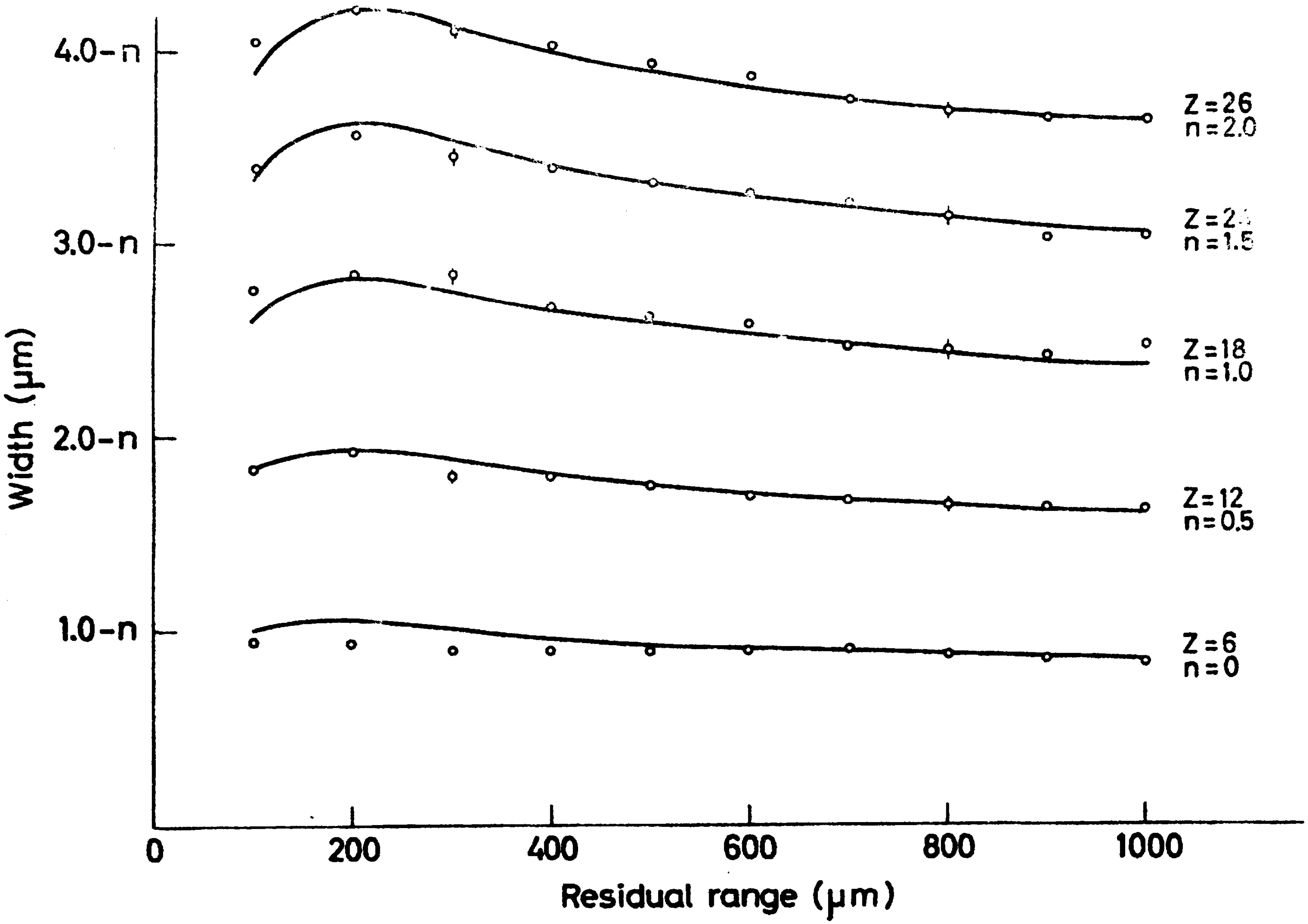
4.0−n
3.0−n
2.0−n
1.0−n
Width (μm)
0
200
400
600
800
1000
Residual range (μm)
Z = 26
n = 2.0
Z = 24
n = 1.5
Z = 18
n = 1.0
Z = 12
n = 0.5
Z = 6
n = 0

Fig. 4a

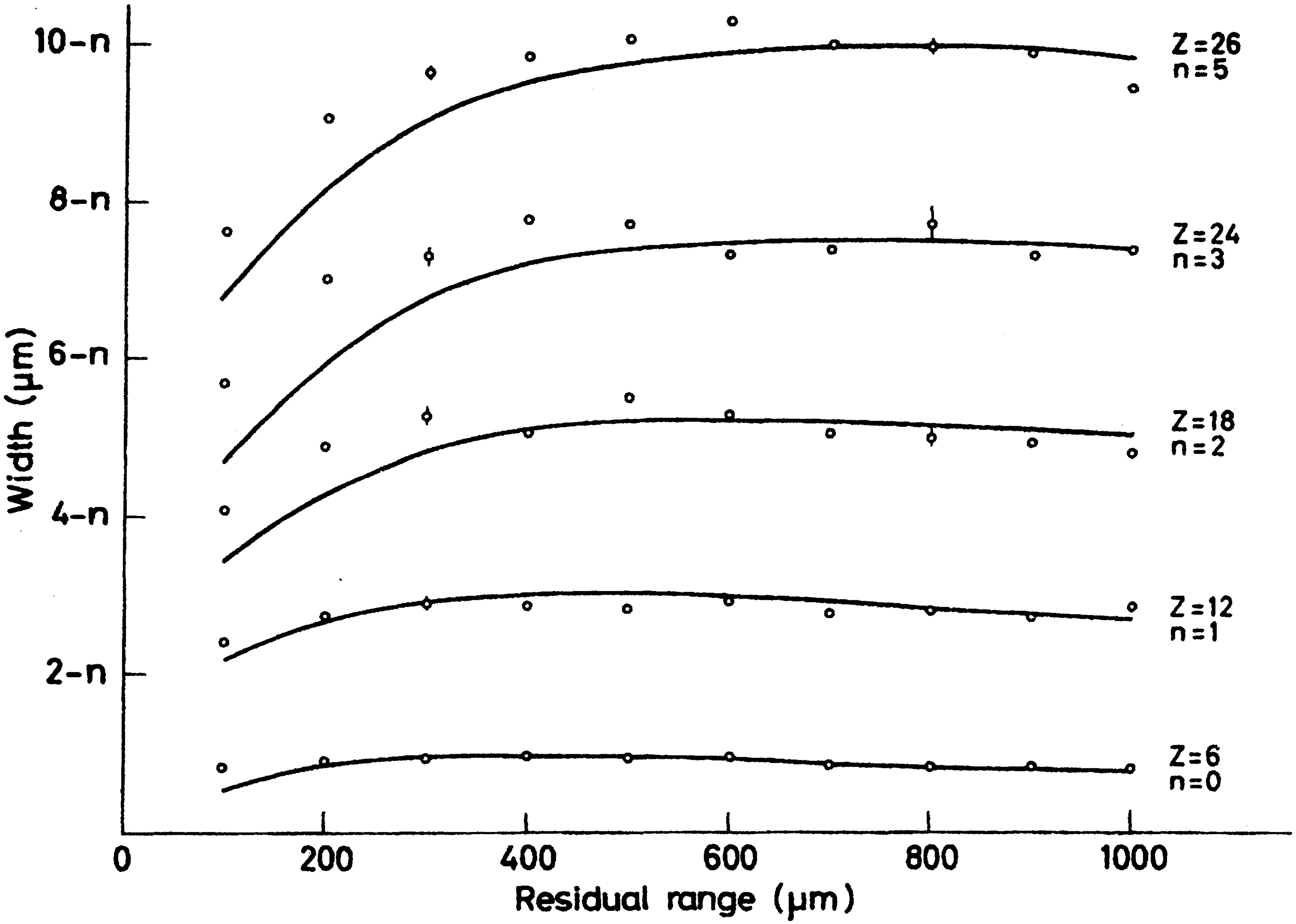
10-n
8-n
6-n
4-n
2-n
Width (μm)
0
200
400
600
800
1000
Residual range (μm)
Z=26
n=5
Z=24
n=3
Z=18
n=2
Z=12
n=1
Z=6
n=0

Fig. 4b