Cosmic Ray Physics Report

LUIP-CR-73-13

November 1973

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CONTENTS

The energy dose concept applied to heavy ion tracks in nuclear emulsion.

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Experimental data on track widths in nuclear emulsion are compared with the theoretical distribution of the energy dose around the path of a moving ion. The dose distribution has been calculated following the formalism of the track formation theory developed by Katz and co-workers. The track widths have been estimated from light absorption profiles of heavy ion tracks. The profiles have been recorded with a nuclear track photometer with a narrow slit. The tracks studied were produced by stopping cosmic ray particles with the charges 6, 12, 18, 24, and 26. The measurements cover the residual range interval $0 < R \leq 1000$ μm, implying ion velocities below 0.33 c. Two types of emulsion with different sensitivity, Ilford G5 and Ilford K2, have been investigated. The measured track widths in K2 are quite well described theoretically, whereas regarding the measurements in G5 there is some disagreement between experimental and theoretical track widths.

Introduction.

Several models for the formation of particle tracks in nuclear emulsion have been proposed (1). The grain density of a track can be described approximately by the average energy loss parameter as given by the Bethe-Bloch energy loss

formula. It is, however, not possible to obtain a unique relation between grain density and ionization. The reason is that at high ion velocities the most energetic secondary electrons (δ-rays) scatter away from the central track region and deposit their energy at the side of the path to an extent which depends on the ion velocity. The next step in the development of a relation between energy loss and grain density was to reduce the influence of the energetic δ-rays on the track parameter, only including the energy deposited by δ-rays of kinetic energy less than some predetermined value. This energy loss parameter is called "restricted energy loss " or REL, and is equivalent to the energy cut-off form of "linear energy transfer" or LET (2). It has been shown that REL is a useful parameter in the description of heavy ion tracks in nuclear emulsions, when working in a limited interval of particle velocities (3).

A new approach to these problems was made by Katz and co-workers (4-6). Modifying a track formation model suggested by Bizzeti and Della Corte (7), they introduced the concept of energy dosage and calculated the energy dose distribution around the path of the particle. The theory has been applied to effects of heavy ion bombardment on various detectors in attempts to understand their response (8-11). It has also been used in studies on interactions between heavy ions and biological systems (12).

The most detailed study of the spatial distribution of ionization energy of a charged, moving particle can be achieved through analyses of tracks in a nuclear emulsion detector. In the present work we have chosen to investigate two types of nuclear emulsion, the electron-sensitive Ilford G5 and the less sensitive Ilford K2. The track widths of heavy ions

have been carefully studied by means of a specially constructed photometer (13) which registers light absorption profiles of track segments. These "track profiles" are then compared to calculations of the spatial dose distribution around the particle's path, following the track formation theory of Katz. Preliminary results have been reported elsewhere (10).

Spatial distribution of ionization energy.

In calculating the energy dose distribution around the path of a heavy ion, we have strictly followed the computational structure presented by Katz and Kobetich (6). Here only a short summary will be given.

A charged particle loses energy to the medium, through which it passes, by collisions with electrons. These electrons are ejected from the target atoms and deposit their energy in the vicinity of the particle's path. In the basic computation of the point distribution of energy deposition, the calculation includes a δ-ray distribution formula differential in energy, an assumed angular distribution and an algorithm fitted to electron dissipation data.

The number of δ-rays with energies between ω and $\omega + d\omega$, $\delta n/\delta\omega$, ejected per unit length of ion path by an ion of speed βc and effective charge Ze, is given by Mott's formula (14):

$$\frac{\delta n}{\delta \omega} = \frac{2\pi \quad NZ^2 e^4}{m \; c^2 \; \beta^2} \quad \frac{1}{\omega^2} \left\{ 1 - \frac{\beta^2 \omega}{\omega_{max}} - \frac{\pi \beta Z}{137} \left(\frac{\omega}{\omega_{max}}\right)^{1/2} \left(1 - \frac{\omega}{\omega_{max}}\right) \right\},$$

where e and m are the electron charge and mass, and N is the density of electrons in the target material. Here only the first term is taken into account in the calculations.

The angular distribution of ejected electrons is assumed to follow classical kinematics according to

$$\cos^2\theta = \frac{\omega}{\omega_{max}} ,$$

where θ is the angle between the ion path and the ejected electron with energy ω. The formula is strictly valid only if $\omega_{max} = 2\ mc^2\beta^2\ (1-\beta^2)^{-1} << 2\ mc^2$, i.e. at $\beta^2 << 0.5$.

In the emulsion, ω is interpreted as the total energy transferred to the bound electron and is equal to the sum of the mean binding energy $\bar{I}$ and the kinetic energy w acquired by the electron:

$$\omega = \bar{I} + w .$$

The energy dissipation of the ejected electrons is computed by the algorithm given in a report by Kobetich and Katz (15). This algorithm uses the characteristic thickness - energy relationship for electrons, giving the residual energy

$$W(r,u) = w(r - u)$$

after penetrating a foil of thickness u; w is the initial energy and r is the characteristic thickness. The energy transmitted through the foil by a single electron is approximated by the product of W and η, the probability of transmission. When applied to nuclear emulsions, it is assumed that the emulsion can be treated as a homogeneous medium.

Integrating the energy dissipation over the δ-ray distribution formula and taking into account the angular distribution of the electrons,we obtain the point distribution of energy dose, E(t), delivered in a shell at distance t from the particle's path.

$$E(t) = -\frac{1}{2\pi t} \int_0^{\omega_{max} - \bar{I}} \frac{\delta}{\delta t} \left[W(t,w,\theta) \cdot \eta(t,w,\theta) \right] \frac{\delta n}{\delta \omega}\ \delta w \quad .$$

The result of such a calculation for a "homogeneous" nuclear

emulsion is given in Fig. 1. The graph shows the radial dose distribution for a singly-charged particle with different values of the velocity β.

Our knowledge of the spatial distribution of the deposited energy, E(t), is used to calculate the mean energy dose $\bar{E}(t)$, averaged over the volume of a sensitive cell. For a nuclear emulsion, approximated as a homogeneous medium, this sensitive cell will be a sphere with the same Ag Br content as an emulsion grain. The radius of the sphere is a_o = 0.17 μm for Ilford G5 and a_o = 0.13 μm for Ilford K2. Calculations of $\bar{E}(t)$ for the two emulsion types is given in Figs. 2 and 3.

Experimental details.

The track widths of heavy ions have been measured using a nuclear track photometer, described by Jacobsson et al. (15). The essential part of the photometer is a microscope with an optical system including a revolving mirror system, a narrow slit and a photomultiplier. The dimensions of the slit correspond to 11.4 x 0.16 μm^2 in the emulsion plane. When the mirror system is turned, the image of a track segment is moved across the slit, which is parallel to the track. In this passage the amount of light reaching the photomultiplier fluctuates and a light absorption profile of the track segment is registered by a pen recorder.

Width measurements of tracks have been made in two nuclear emulsion stacks exposed to the primary cosmic radiation. The two stacks are of different sensitivity, one consisting of Ilford G5 and the other of Ilford K2 emulsion plates. About 40 tracks with a mean dip angle of 4^o were included in our investigation. The tracks were produced by particles

with the nuclear charges Z=6, 12, 18, 24 and 26, stopping in the emulsion. The charges of the particles had been determined by photometrical methods in earlier investigations (16-18).

Absorption profiles were registered for each track at every 10 microns in the residual range intervals 10-120, 180-220, ----- 980-1020 µm. Fig. 4 shows some examples of such profiles. For every profile a base line was drawn representing the light background in the emulsion pellicle. The width of the profiles was determined at different levels above the base line, each level corrresponding to a certain degree of light absorption.

Comparison with theoretical track profiles.

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:

$$P(t) = 1 - \exp(-\bar{E}(t)/E_o),$$

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 counts in tracks of weakly ionizing particles (6). For the Ilford G5 emulsion the value was found to be $E_o = 4 \cdot 10^4$ erg/cm^3, and for the Ilford K2 emulsion, $E_o = 6 \cdot 10^5$ erg/cm^3. The characteristic dose depends on the sensitivity and on the processing conditions of the emulsion.

In Ilford K2 emulsion a track shows a well defined core with some δ-rays jutting out of it. For the theoretical calculation of the track width it is assumed that the track is defined by a cylinder of radius x, inside which the dose $\bar{E}(t)$ exceeds a critical limit E_c. During the development, the diameter of a developed grain will increase by a certain amount, depen-

ding on the type of emulsion and on the conditions of processing. The effect of the development on the track width can be accounted for by an additive term λ_o. The track width after processing will be $\lambda = 2x + \lambda_o$.

Theoretical track widths have been calculated for different values of the parameters, E_c and λ_o. These widths have been compared with the profile widths at half the profile height. The best agreement between theoretical and measured values was obtained for the critical dose $E_c = 75000$ erg/cm^3 and $\lambda_o = 0.4$ μm. The measured track widths for different charges are shown in Fig. 5, together with theoretical track width curves. As can be seen from the graph, the measured track widths are very well described by the theory. The agreement covers the whole charge interval $6 \leq Z \leq 26$ and the residual range interval $100 \leq R \leq 1000$ μm. Theoretical calculations using suitable parameter values can also be reconciled with profile widths at other absorption levels.

In Ilford G5 emulsion, the core is surrounded by a large number of δ-ray grains. These grains, lying at different depths in the emulsion, contribute to the light absorption. Accordingly the absorption must be considered as a function of the number of developed grains within a volume enclosing the track. The absorption of light, passing parallel to the Z-axis at a distance x from the track centre, can be described by a function

$$F(x) = 1 - \exp\left[-\alpha AG \int_{Z_1}^{Z_2} P(t)dz\right] , \quad t^2 = x^2 + z^2 ,$$

where $G = 49$ μm^{-3} is the density of undeveloped grains.

$A = 0.28\ \mu m^2$ is the mean projected area of a developed grain and α is a multiplying factor to the geometrical cross-section. The integration of the probability parameter, P, is performed within a depth interval Z_1 and Z_2, in which the photometer registers the silver grains belonging to the track. This method of calculation implies that the photometer works with a beam of parallel light. However, this is not true, though an investigation has shown that the measured track widths are almost insensitive to the shape of the light cone.

The function F(x) describes theoretical absorption profiles with absorption values between 0 and 1, where 1 implies total absorption. The measured light absorption cannot be compared directly with the theoretical values. This depends on the light scattering in the emulsion, which influences the registration of the light absorption. To compensate for this effect all the profiles were normalized to the same height where the absorption was set equal to 1. This can be justified by the fact that the track core is compact and has no gaps. The profile widths at four different absorption levels 1/3, 1/2, 2/3 and 5/6 have been compared with the calculations of F(x). The multiplying factor α in F(x), which is intended to accomodate optical effects, was then treated as an adjustable constant. The comparison shows that it is not possible to get a satisfactory description of the measured profile widhts in the whole range and charge interval. We have chosen to make a fit which gives the best agreement for the experimental widths of the low charges, Z= 6 and Z=12. In Fig. 6 the theoretical width is compared with the profile width at half the profile height. For the absorption level equal to 5/6, the comparison is shown in Fig. 7. The theoretical curves in

these Figures are calculated for $\alpha = 0.42$ and $\lambda_c = 0.4$ μm. The development correction λ_o has in Ilford G5 emulsion less importance than in Ilford K2 owing to the greater track widths. In Fig. 6 there is a clear disagreement between the measured and calculated half-width for the charges $Z \geq 18$. It is not possible to adjust the parameters, α and λ_o, to reach agreement for these charges in a large range interval. A somewhat better agreement is obtained for the profile width at an absorption level equal to 5/6 as shown in Fig. 7. For the range interval 600 - 1000 μm there is good agreement for all the charges. However, for $R \leq 400$ μm it is not possible to explain the experimental track width of the charges $Z \geq 18$ from the assumptions made in the theory.

Fig. 8 shows the measured light absorption as a function of the lateral distance from the track axis together with calculated relations for the charges $Z = 6$ and $Z = 26$ and for the residual ranges $R = 200$, 600, and 1000 μm. The graphs indicate that the theory fails to explain the distribution of grains far from the track centre. This is most pronounced for the high charges. The reason may be that the calculations of the energy dose do not take properly into account the scattering of the electrons. Further, a more thorough description of the light scattering in the emulsion may give a somewhat better consistency. In the calculation of theoretical track profiles, Mathiesen has introduced a new light-scattering parameter and a modified angular distribution of the δ-rays (19). Good accordance with theory was then obtained for profiles of iron tracks at ion velocities $\beta \geq 0.3$. Preliminary results for the charges $Z = 14$, 16, 20, 24, and 26 and $\beta = 0.3 - 0.7$ show acceptable agreement with calculated profiles in the whole

β-interval (20).

Our results show that the track formation theory developed by Katz and co-workers gives quite a good description of the track width for the non-electron sensitive Ilford K2 emulsion. However, the theory cannot be used without modifications for the description of heavy ion tracks in the electron sensitive Ilford G5 emulsion in the residual range interval $0 < R \leq 1000$ μm.

Acknowledgement

The authors wish to express their sincere gratitude to Prof. K. Kristiansson for much advice and valuable discussions. The research reported in this document has been sponsored in part by the Swedish Natural Science Research Council, which is gratefully acknowledged.

Figure captions.

Fig. 1. The point distribution of energy dose, $E(t)$, divided by Z^2, as a function of the distance t from the particle path. Calculation for a "homogenous" nuclear emulsion.

Fig. 2. The mean energy dose, $\bar{E}(t)$, divided by Z^2, averaged over the volume of a sensitive cell with the radius a_o = 0.13 μm for Ilford K2.

Fig. 3. The mean energy dose, $\bar{E}(t)$, divided by Z^2, averaged over the volume of a sensitive cell with the radius a_o = 0.17 μm for Ilford G5.

Fig. 4. Examples of absorption profiles for ion charge Z = 25 from the measurements in Ilford G5 (to the left) and Ilford K2 (to the right). Observe the different scales.

Fig. 5. Track widths at half the profile height for different charges from the measurements in the Ilford K2 emulsion stack.
The theoretical curves are calculated for the critical dose E_c = 75000 erg/cm^3 and λ_o = 0.4 μm.

Fig. 6. Track widths for different charges from the measurements in the Ilford G5 emulsion stack together with theoretical curves calculated for the parameter values α = 0.42 and λ_o = 0.4 μm. Absorption level equal to 1/2.

Fig. 7. Track widths for different charges from the measurements in the Ilford G5 emulsion stack together with theoretical curves calculated for the parameter values $\alpha = 0.42$ and $\lambda_o = 0.4$ μm. Absorption level equal to 5/6.

Fig. 8. The light absorption from the measurements in the Ilford G5 emulsion stack plotted as a function of the lateral distance from the track axis. The theoretical curves are calculated for the parameter values $\alpha = 0.42$ and $\lambda_o = 0.4$ μm.

References.

1) W.H. Barkas, Nuclear Research Emulsions, Vol. 1, Academic Press, New York (1963).

2) Linear Energy Transfer, ICRU Report nr 16, International Commission on Radiation Units and Measurements.

3) M. Jensen, L. Larsson and R. Rosander, Nucl. Instr. Meth. 104, 611 (1972).

4) R. Katz and J.J. Butts, Phys. Rev., 137, 198 (1965).

5) E.J. Kobetich and R. Katz, Phys. Rev., 170, 405 (1968).

6) R. Katz and E.J. Kobetich, Phys. Rev., 186, 344 (1969).

7) P.G. Bizzeti and M. Della Corte, Nuovo Cimento, 11, 317 (1959).

8) Y.K. Lim and K. Fukui, Nucl. Instr. Meth., 44, 261 (1966).

9) R.K. Gaur and A.P. Sharma, Indian. J. pure appl. Phys.,8, 468(1970).

10) R. Rosander and L. Jacobsson,
Proc. 8th Int. Conf. Nucl. Phot. SSTD,
Bucharest 1972, to be published.

11) R. Katz, S.C. Sharma and M. Homayoonfar,
Nucl. Instr. Meth., 100, 13 (1972).

12) R. Katz, B. Ackerson, M. Homayoonfar, and S.C. Sharma,
Radiation Research, 47, 402 (1971).

13) L. Jacobsson, G. Jönsson, K. Söderström and H. Håkansson,
Nucl. Instr. Meth., 112, 575 (1973).

14) H.L. Bradt and B. Peters,
Phys. Rev. 74, 1828 (1948).

15) E.J. Kobetich and R. Katz,
Nucl. Instr. Meth., 71, 226 (1969).

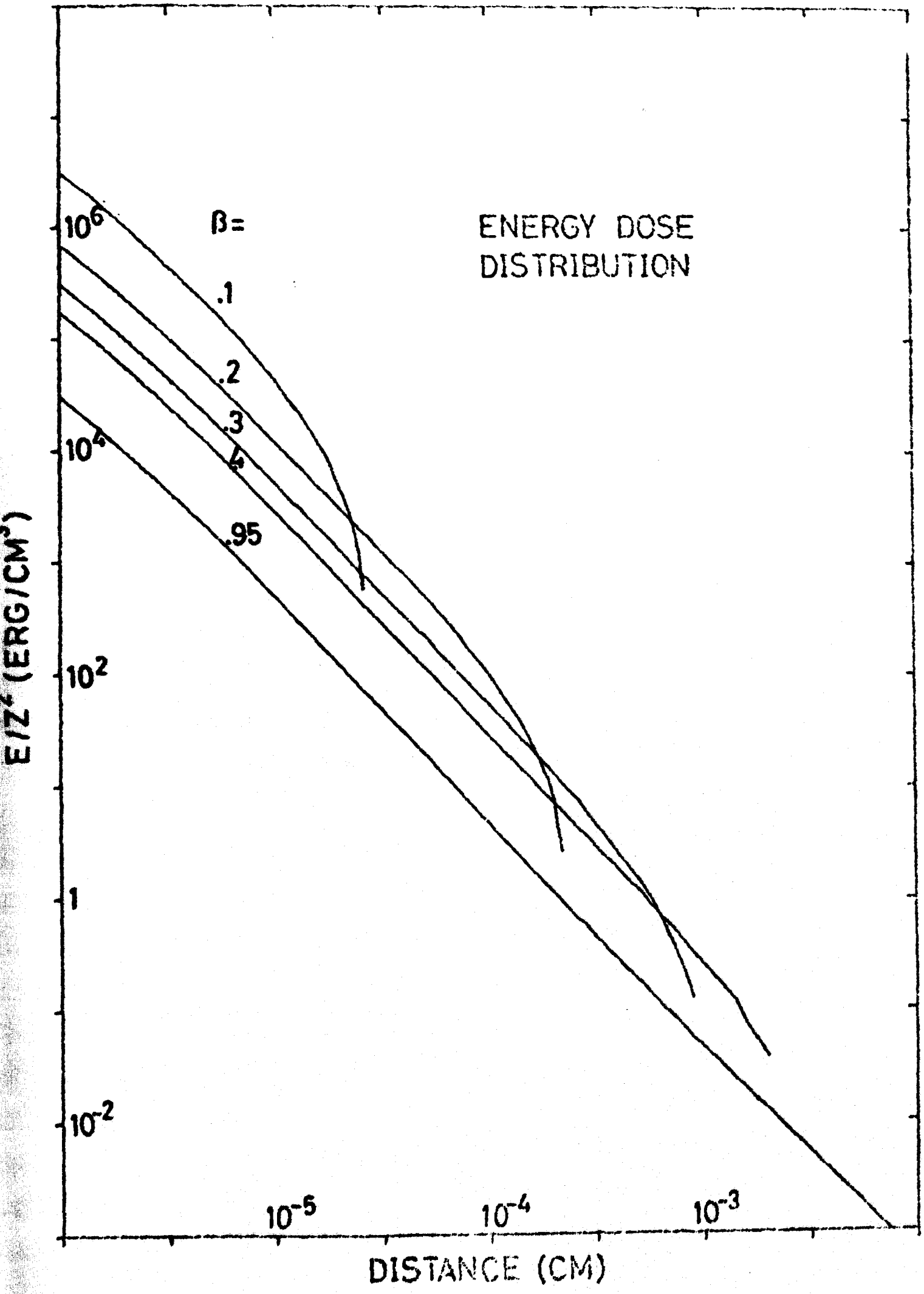
16) G. Jönsson, K. Kristiansson and L. Malmqvist,
Astrophys. Space Sci., 7, 231 (1970).

17) U. Dellien, K. Söderström and K. Kristiansson,
Astrophys. Space Sci., 8, 74 (1970).

18) R. Rosander,
Nucl. Instr. Meth., 100, 149 (1972).

19) O. Mathiesen,
Proc. 8th Int. Conf. Nucl. Phot. SSTD,
Bucharest 1972, to be published.

20) M. Jensen, L. Larsson, O. Mathiesen and R. Rosander,
Conf. Papers, 13th Int. Cosm. Ray Conf.,
Volume 4, p.2942, Denver, U.S.A. 1973.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.2
.3
.4
.95
10^6
10^4
10^2
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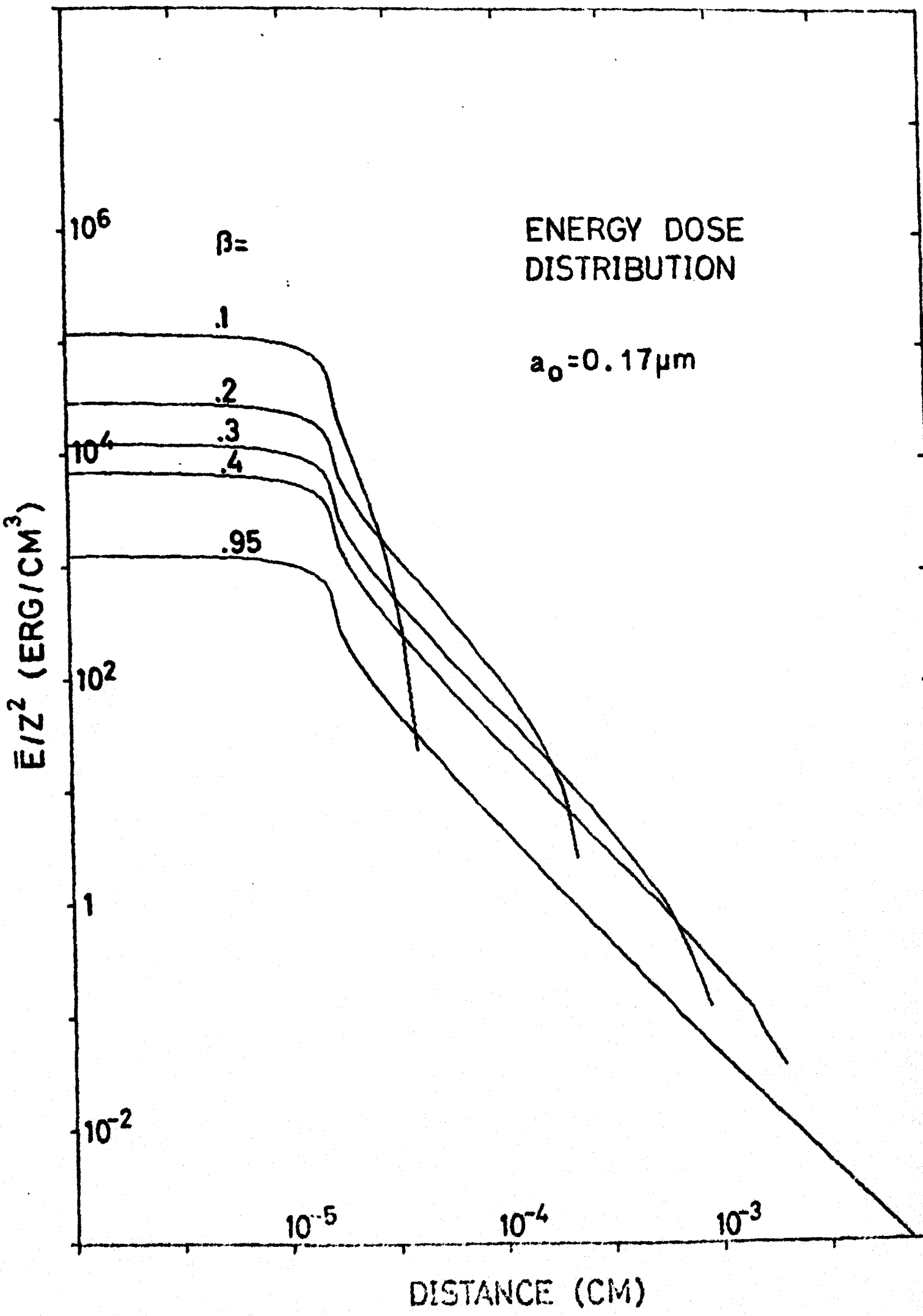
10^{-5}
10^{-4}
10^{-3}
DISTANCE (CM)
E/Z² (ERG/CM³)

Fig.1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.2
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10^4
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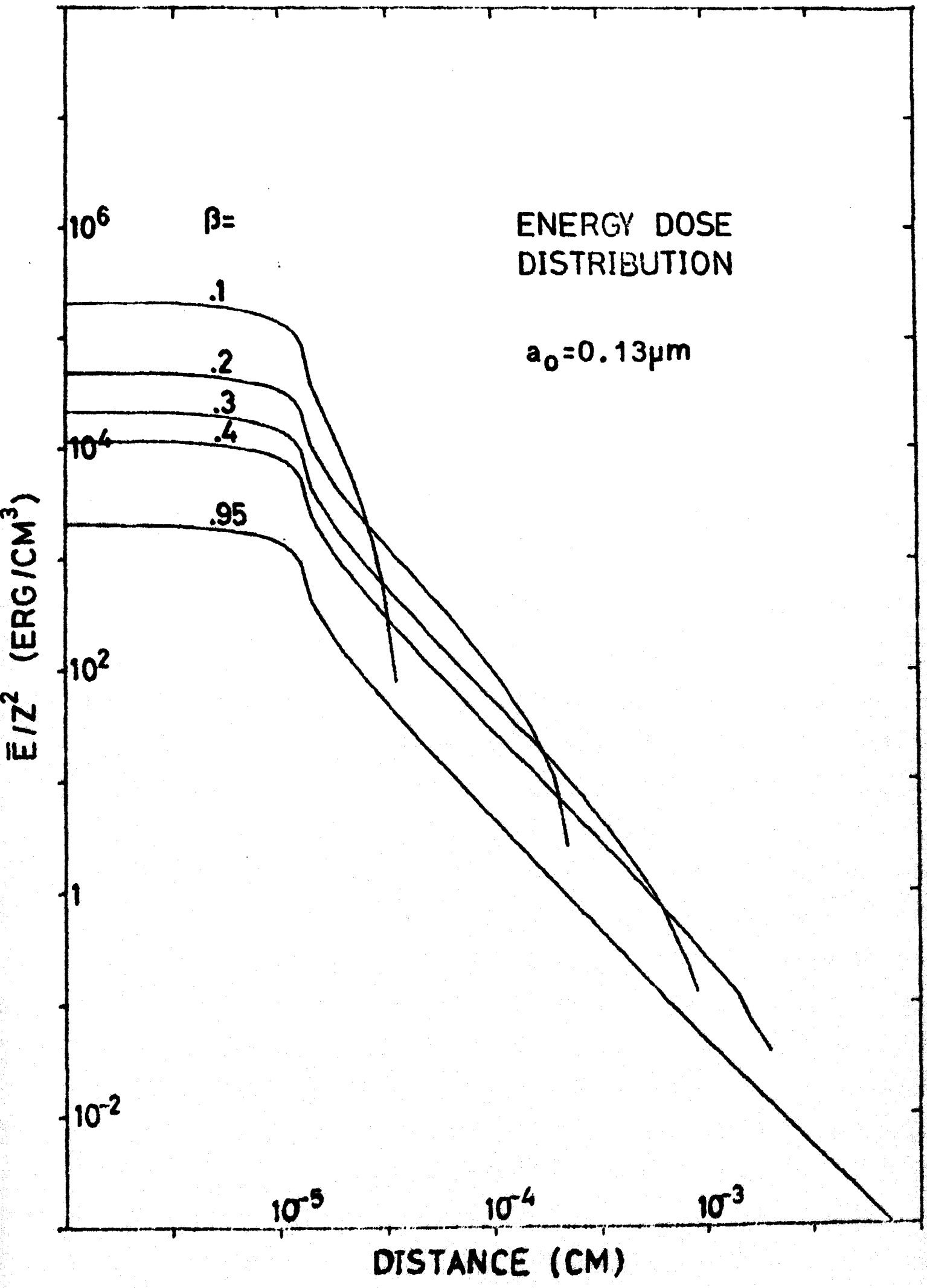
10^{-5}
10^{-4}
10^{-3}
DISTANCE (CM)

Fig.2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10^6
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E/Z^2 (ERG/CM^3)
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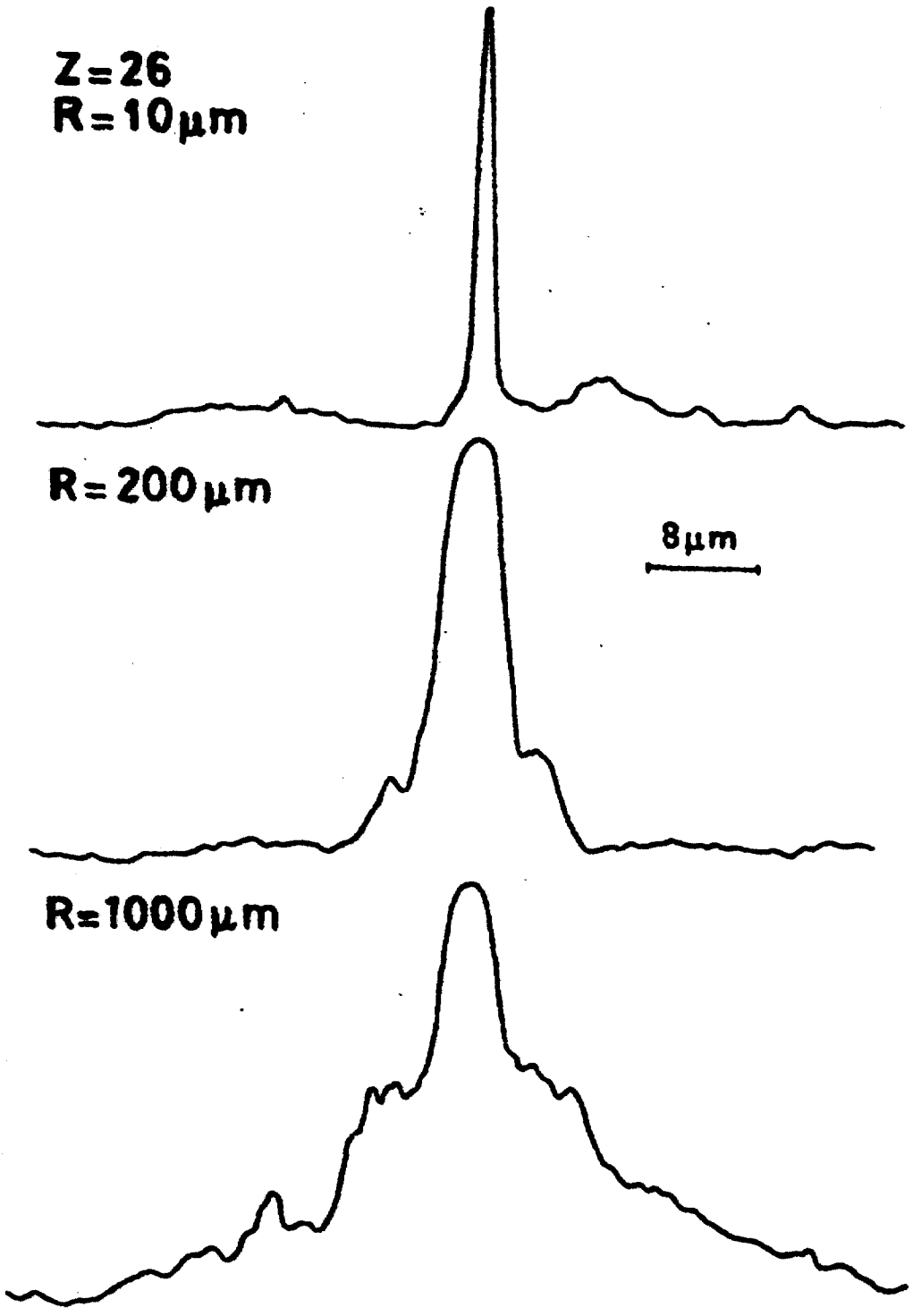
10^{-4}
10^{-3}
DISTANCE (CM)

Fig.3



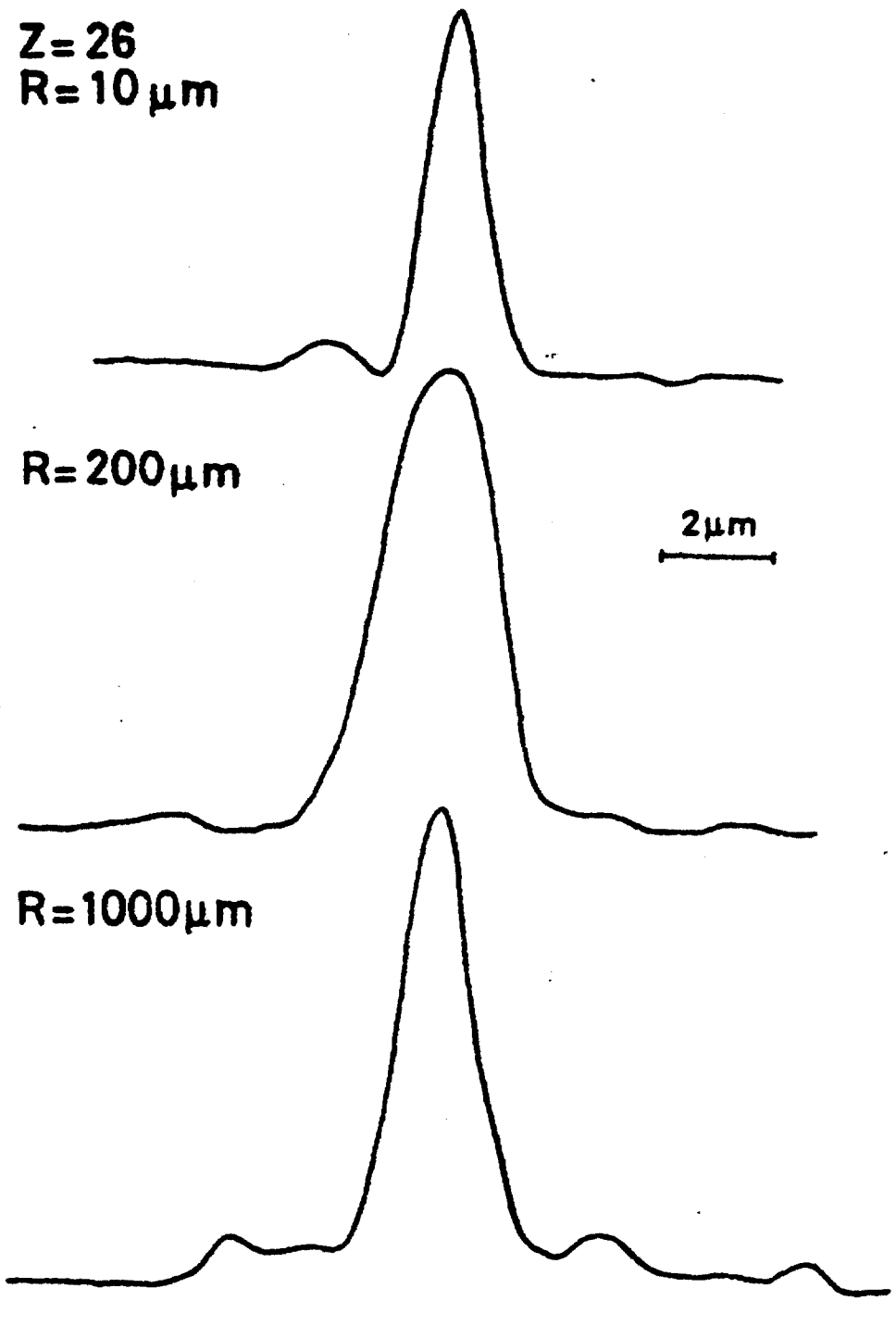
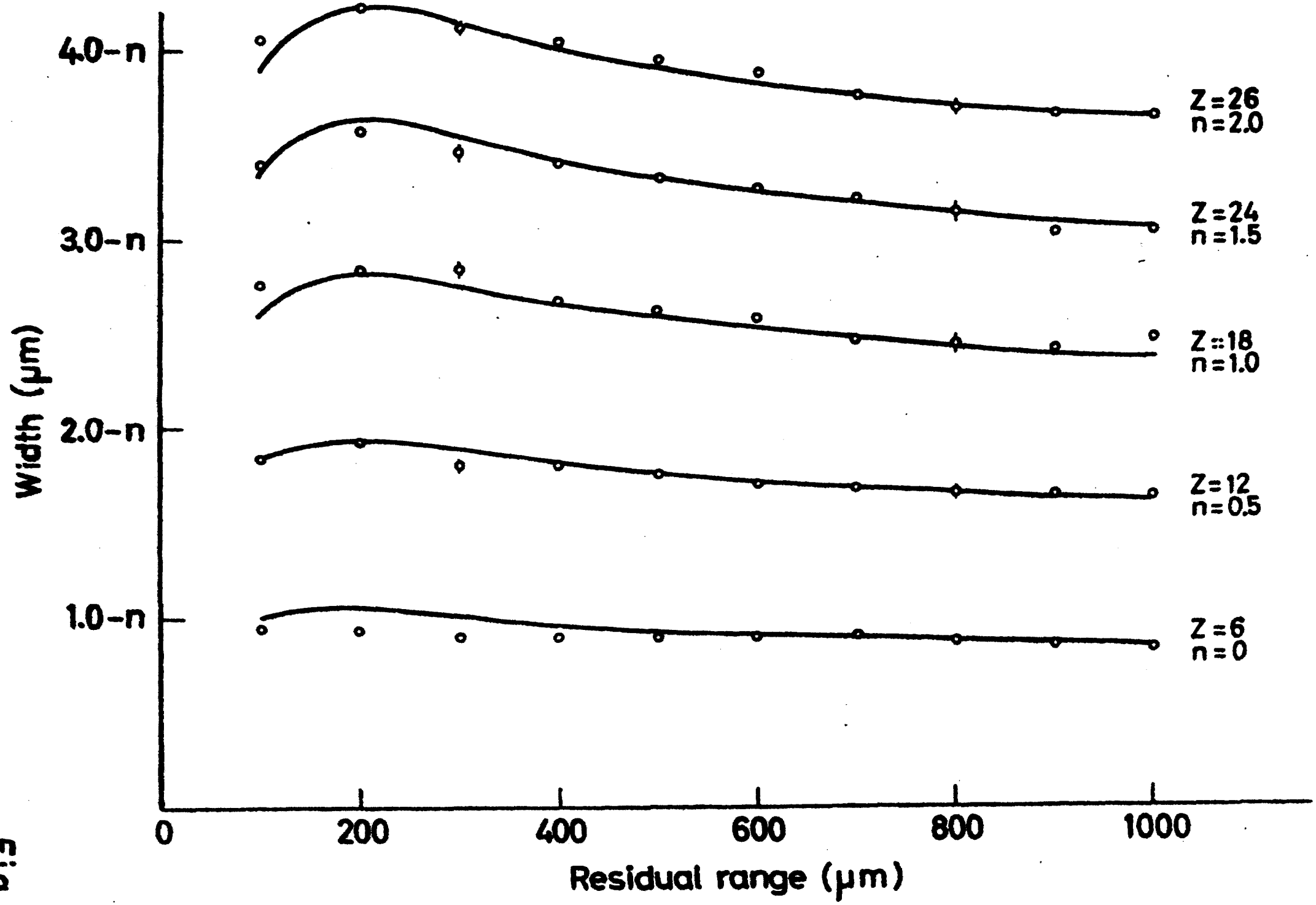


Fig.4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3.0-n
2.0-n
1.0-n
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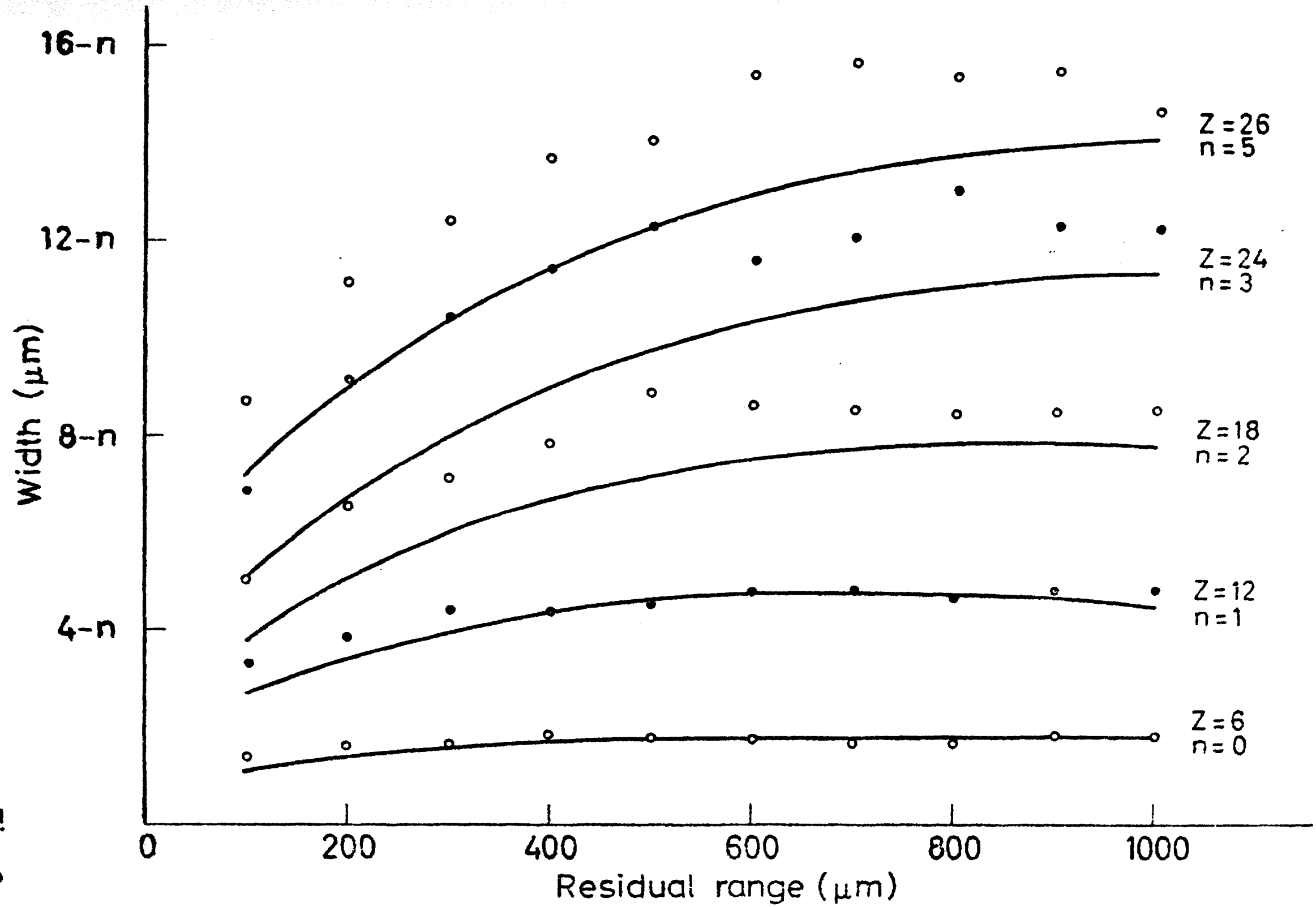
Z=24
n=1.5
Z=18
n=1.0
Z=12
n=0.5
Z=6
n=0
0
200
400
600
800
1000
Residual range (μm)

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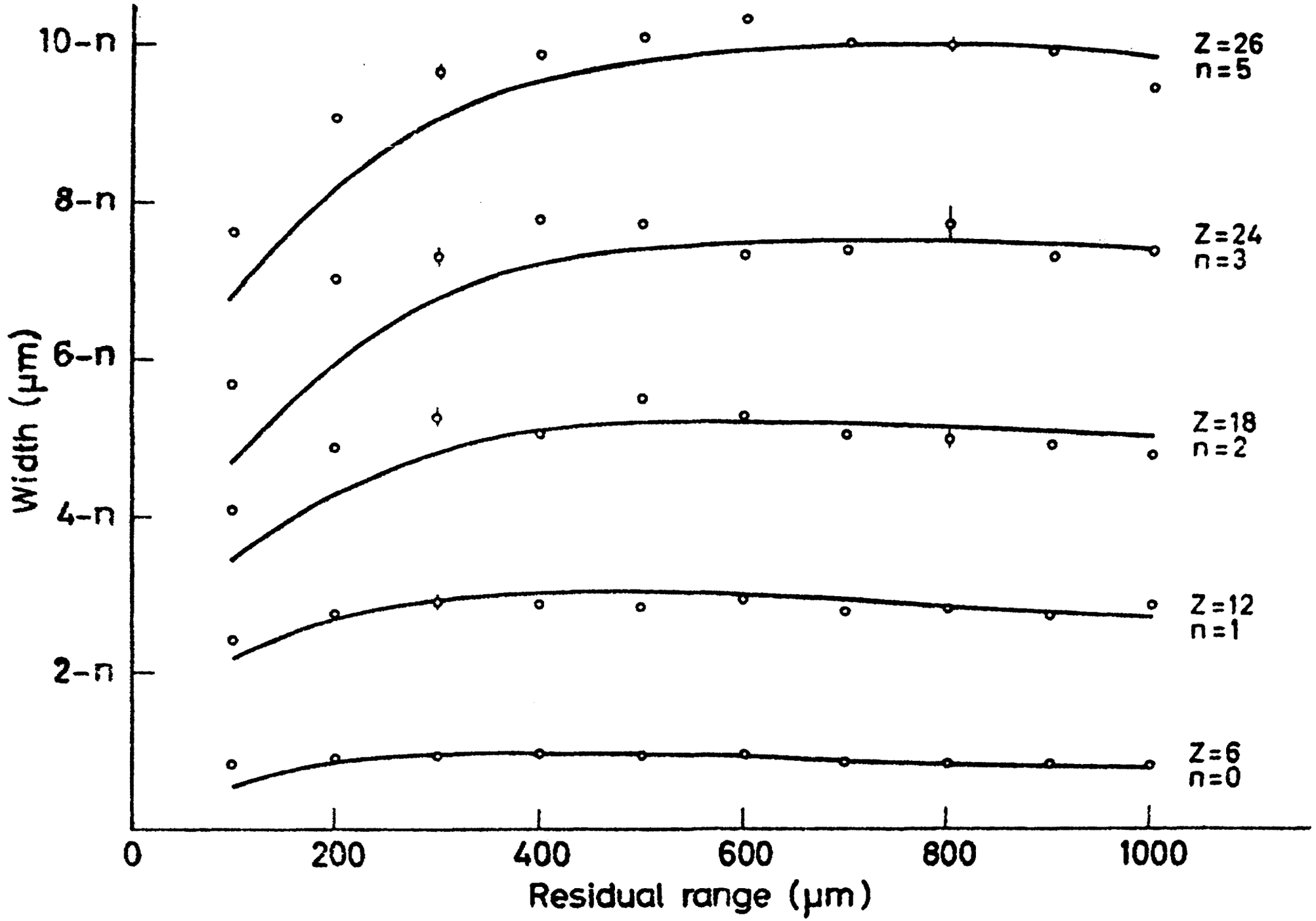
n = 1
Z = 6
n = 0
0
200
400
600
800
1000
Residual range (μm)

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

Fig. 7

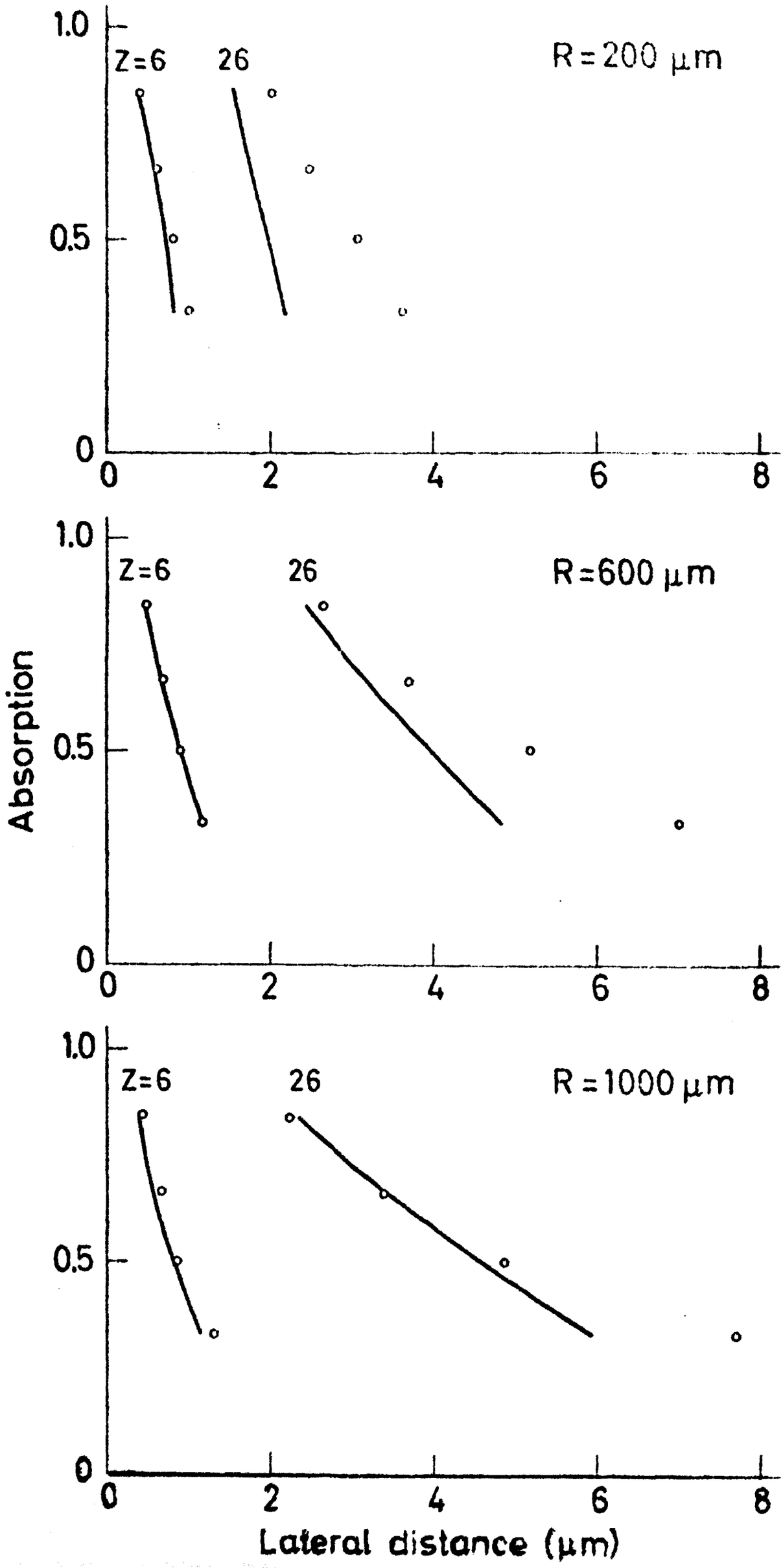
1.0
0.5
0
Z=6
26
R=200 μm
R=600 μm
R=1000 μm
Absorption
0
2
4
6
8
Lateral distance (μm)

Fig. 8