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ON THE FORMATION OF TRACKS OF FAST HEAVY IONS IN NUCLEAR EMULSION

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Submitted to the
COUNCIL OF EUROPE, Working Party on Space Biophysics,
Meeting 4-6 October 1973. Fontenay-aux-Roses, France.

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Abstract

A detailed study of the tracks of fast, heavy ions in an electron-sensitive nuclear emulsion of type Ilford G5 have been carried out. Using a nuclear track photometer with a narrow slit we have registered transverse absorption profiles on 27 tracks of nuclei with charge numbers 14, 16, 20, 24 and 26, covering the velocity interval 0.3c to 0.8c. The charges of the heavy nuclei, emanating from the cosmic radiation, were determined earlier by photometric methods.

Theoretical track profiles were computed from the distribution of energy dose around the path of a passing ion. This dose distribution was evaluated according to the delta-ray theory of track structure developed by Katz and co-workers. Utilizing a parameter optimization algorithm, the calculated profiles were fitted to the experimental data. From this comparison we can conclude that a reasonable agreement between experimental and calculated profiles can be obtained if we can adequately compensate for the backscattered light in the emulsion.

Une étude photométrique de la structure des traces des ions lourds rapides de la radiation cosmique, enregistrées dans les émulsions nucléaires, est présenté dans le travail suivant. Les mesures obtenues ont été comparés avec les calculs de la distribution d'énergie déposée autour de la trajectoire d'un ion en mouvement.

Nous avons montré que, si l'on tient compte de la diffusion de la lumiére dans l'émulsion, le concept d'énergie déposée peut donner une déscription satisfaisante des données experimentales.

Introduction

In this paper we wish to discuss some recent experimental results concerning the formation of heavy ion tracks in nuclear emulsion . The observational data are obtained from studies of cosmic ray nuclei recorded in electron-sensitive Ilford G5 nuclear emulsions, exposed to cosmic radiation by means of a stratospheric balloon.

Current ideas about track formation in nuclear emulsion emanate from the early work by Bizzeti and Della Corte (1). These authors formulated a theory for the last part of the track of a heavy ion, based on the idea that track effects arise principally from the interaction of secondary electrons with the detector. During the last few years this model has been modified and further developed by Katz and his co-workers (2-4) to obtain a theory which would be applicable to particles of all velocities and would describe the response of a number of physical, chemical and biological systems (5). Up to now very few attempts have been made to compare this theory with experimental data (6,7). Considering the potential use of Katz´ theory for calibration purposes in cosmic ray experiments we thus deemed it necessary to initiate a program in which the theory is compared with the observed track structure in nuclear emulsion. The first study, presented at the Bucharest conference last summer (8), dealt with heavy ion tracks at velocities below 0.3c. The measurements were made in two types of nuclear emulsion with different sensitivities, using a nuclear track photometer. The best fit to Katz´ theory was found for the less sensitive Ilford K2 emulsion, while for the electron-sensitive Ilford G5 emulsion the theoretical track widths could not be reconciled with the experimental data. In another report to the Bucharest conference (9) it was shown that a reasonable fit to observations of iron tracks in underdeveloped Ilford G5 emulsion can be obtained if a further parameter is incorporated into the theory. This parameter is thought to accomodate for the influence of the backscattered light in the emulsion.

In this report we present some results of a more comprehensive study based on tracks of particles with charge numbers 14, 16, 20, 24 and 26 and velocities in the interval from 0.3c to 0.8c. Some preliminary results of this study were reported at the Denver conference this year (10).

Experimental details and measurements

In the present study we have used a nuclear emulsion detector consisting of 65 Ilford G5 pellicles. The study is based on a number of tracks of heavy nuclei with known residual range. The particle charge has been determined by Söderström et al (11). The tracks were selected in order to minimize systematic errors owing to dip, processing, and light scattering. Measurements of the tracks were made by a nuclear track photometer described by Jacobsson et al (12). A sketch of the photometric apparatus is displayed in Figure 1. During the readings the image of the track segment was moved perpendicularly across a narrow slit. The transmission of light was measured at 1 micron intervals out to a lateral distance of about 85 microns to both sides of the track axis, giving rise to a "track profile" (Figure 2). The light transmission for each profile is automatically recorded in digital form on paper tape. A block diagram showing the electronic equipment is seen in Figure 3.

The number of tracks of particles with different charge and velocity is shown in Table 1. For numerical reasons all resulting data points, about 84,000 in number, could not be used in the comparison with the theory. The data were reduced and smoothened by computer analysis to give transmission values at six lateral distances: .5, 1.5, 4.5, 8.5, 13.5 and 39.5 microns from the track centre. In a second step of reduction and smoothening mean transmission values at given charge and lateral distance were obtained for five velocity values: .3, .4, .5, .6 and .7 times the velocity of light. This leaves us with 30 data points for each charge number or 150 reduced data points altogether. These were used for the test of the theoretical model for track formation.

Calculation of theoretical track profiles

In the calculation of the energy dose distribution around the path of a heavy ion, we have in general followed the delta-ray theory developed by Katz and coworkers (4). However, we assume that all secondary electrons are ejected normally to the ion trajectory (9). The transmission of parallel light, T_p, through the emulsion is computed from the probability distribution for the development of emulsion grains (4). To compensate for the backscattered light in the emulsion, a model for high aperture photometry is constructed by assuming that the observed absorption, $1 - T$, can be found from a power series expansion in $1 - T_p$, the absorption of parallel light. Thus we can express the absorption as

$$1 - T = a_o + a_1(1 - T_p) + a_2(1 - T_p)^2 + \dots\dots$$

So far in this study we have considered three special cases, as can be seen in Table 2. The theoretical profiles have been fitted to the experimental points by means of a parameter optimization algorithm. The quantity minimized by the procedure is the sum of squares of the differences between calculated and experimental data. This quantity for the three cases studied can also be found in Table 2.

In the original theory Katz uses two fundamental constants: E_0, which is the characteristic dose for sensitization and development of 63 % of the emulsion grains in a uniform exposure, and α, which is a multiplying factor to the geometrical cross-section, intended to accomodate for Rayleigh scattering in the emulsion, owing to the small dimension of the grains. For the emulsions used in the present study we have determined E_0 by counting the grains in the tracks of weakly ionizing particles as described by Katz (4). The value of E_0 was found to be 10.5 keV μm^{-3}.

Results and discussion

Fig. 4a and b show the fitted profiles for case 1 together with the data points for Z = 14 and 26. The fit has been made for all five velocities and for all Z values. The results obtained for the other charge numbers resemble closely those given for Z = 14 and 26. The value obtained for the constant a_2 was -0.22.

In case 2, a_1 was treated as an adjustable parameter. In this case, as in Katz´ original model, light backscattered into the cone of acceptance is not taken into account. This fit gave a squaresum 65 % higher than in case 1.

The parameters obtained for case 3 are given in Table 2. It is reasonable to expect a low value for a_0, to which we assign no physical significance, and values for a_1 and a_2 similar to those of case 1. From the results of case 3 we conclude that, in all essentials, the physical interpretation of the theoretical model of case 1 is justified.

In recent years the model for track formation developed by Katz and co-workers has been applied to a variety of biological detection systems (5,13). The analysis of results from these fields calls for an understanding of several new biophysical properties, such as inactivation statistics and size of the sensitive elements. We feel that, while the track formation model may be successfully developed in new areas of research, the outstanding spatial resolution of the nuclear emulsion still offers the best possibility of a detailed check of the basic elements of the model.

The work reported here will continue. The physical interpretation of the terms of the given formula gives us a possibility to distinguish between the emulsion response to the passing ion and the photometer response to the track structure. Efforts will be made in order to improve the theory in both areas.

Table 1

THE NUMBER OF TRACKS USED AT EACH β AND Z

Z β	0.30	0.40	0.50	0.55	0.60	0.65	0.70	0.75	0.80
14	3	4	4	4	4	5	4	2	-
16	3	3	4	4	4	4	3	-	-
20	2	2	4	4	5	4	3	-	-
24	3	-	3	4	3	4	3	-	-
26	3	5	6	5	6	6	6	6	5

Table 2

case	a_0	a_1	a_2
1	0 (fixed)	1 (fixed)	-0.22
2	0 (fixed)	0.83	0 (fixed)
3	0.015	0.93	-0.16

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Figure captions

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

Fig. 2. Segment of a track in nuclear emulsion and the corresponding transmission profile.

Fig. 3. Block diagram showing the arrangement of the electronic equipment.

Fig. 4a-b. Comparison between calculated absorption profiles and experimental data.

a. $Z = 14$
b. $Z = 26$

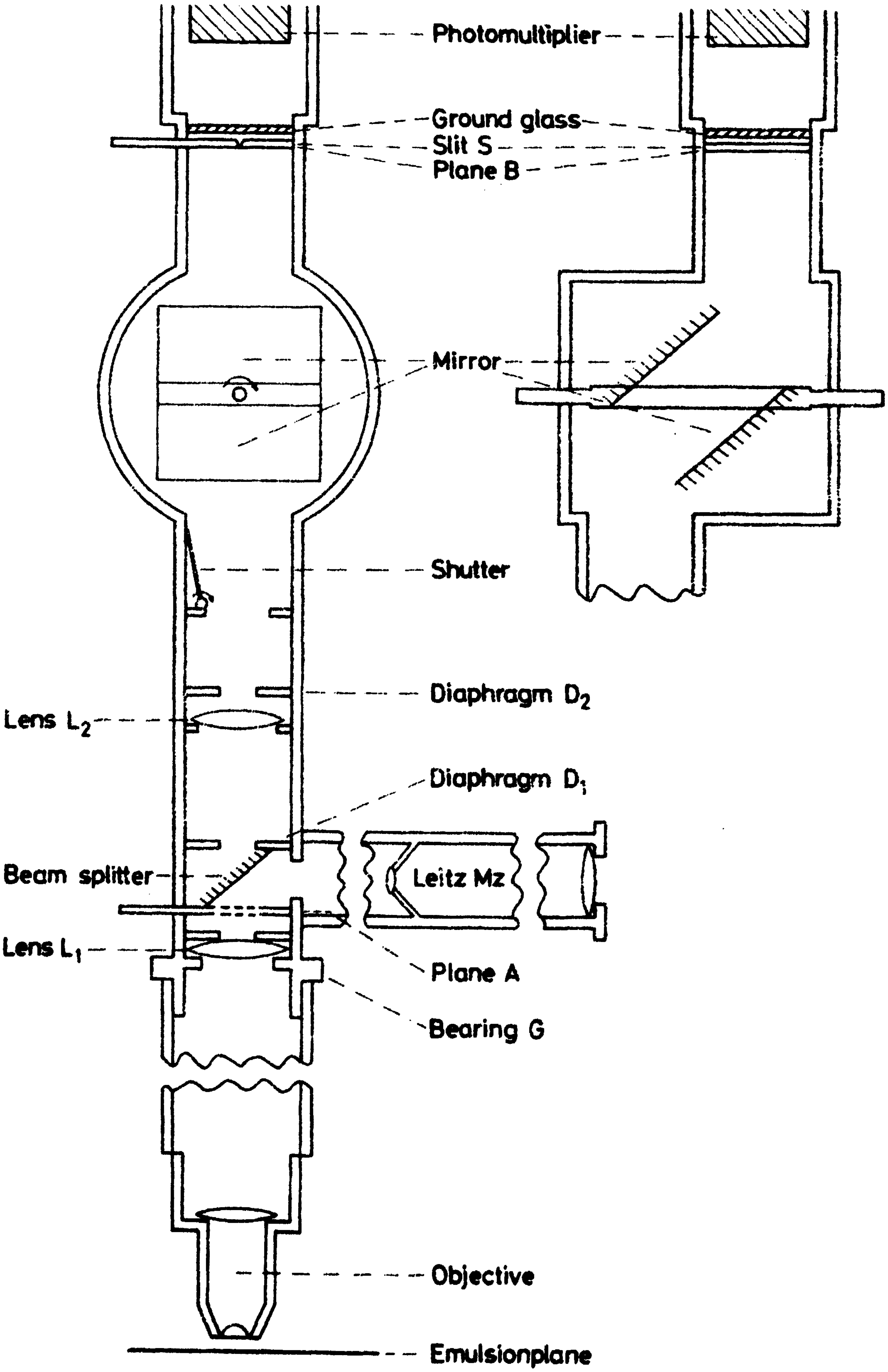
Photomultiplier
Ground glass
Slit S
Plane B
Mirror
Shutter
Diaphragm D_2
Lens L_2
Diaphragm D_1
Beam splitter
Leitz Mz
Lens L_1
Plane A
Bearing G
Objective
Emulsionplane

Fig. 1

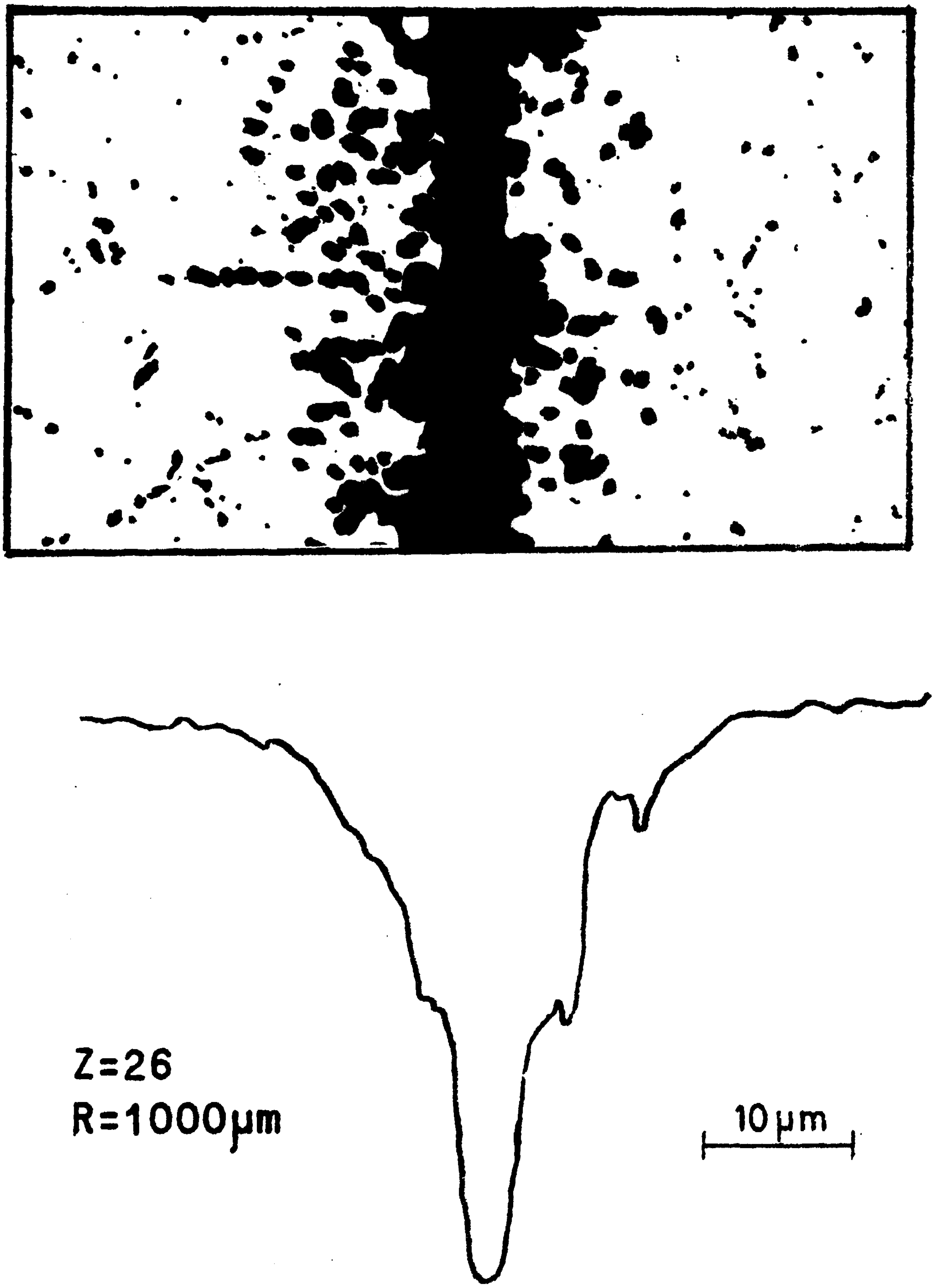

Fig. 2

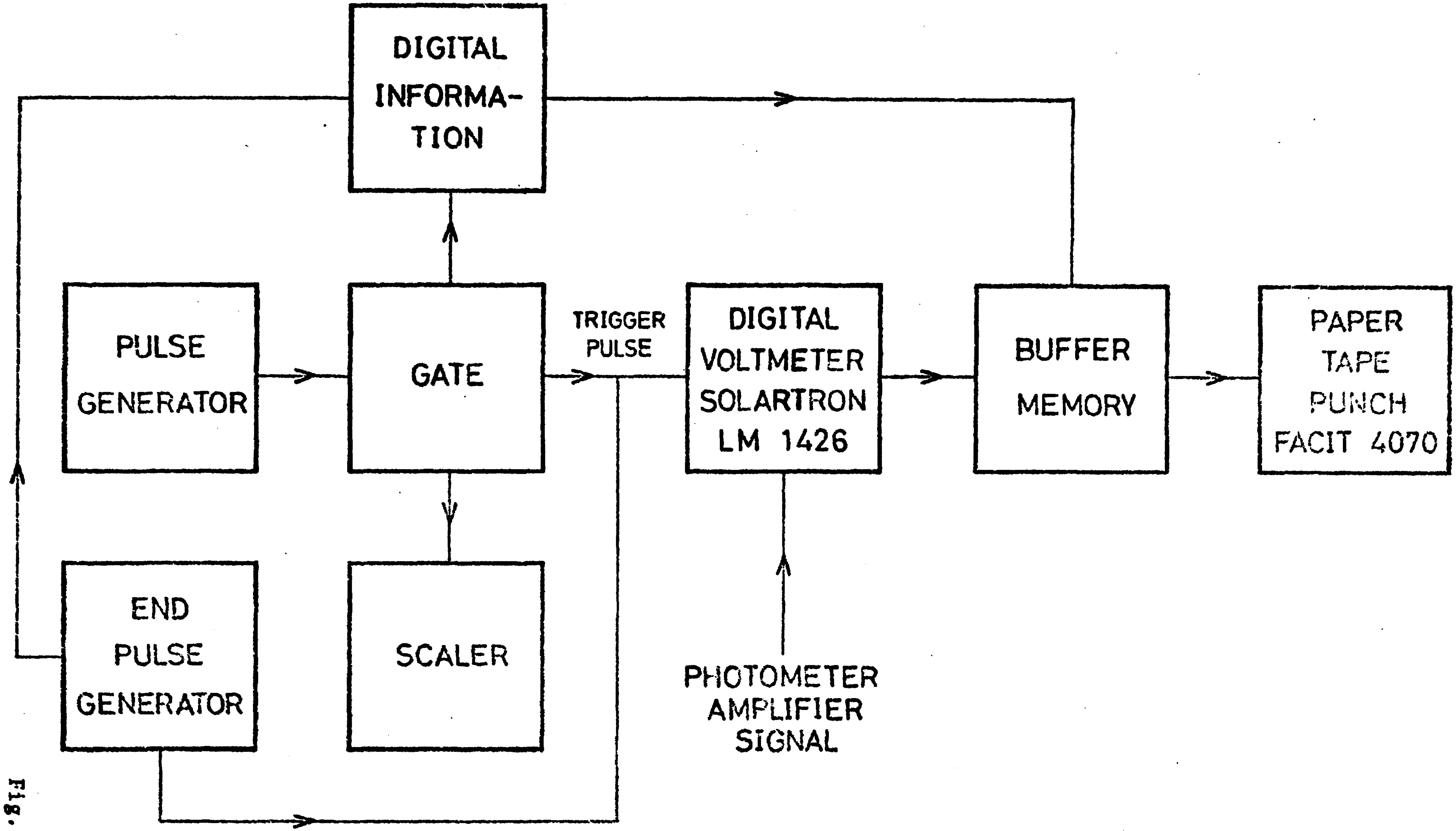
DIGITAL INFORMATION
PULSE GENERATOR
GATE
TRIGGER PULSE
DIGITAL VOLTMETER SOLARTRON LM 1426
BUFFER MEMORY
PAPER TAPE PUNCH FACIT 4070
END PULSE GENERATOR
SCALER
PHOTOMETER AMPLIFIER SIGNAL

Fig. 3

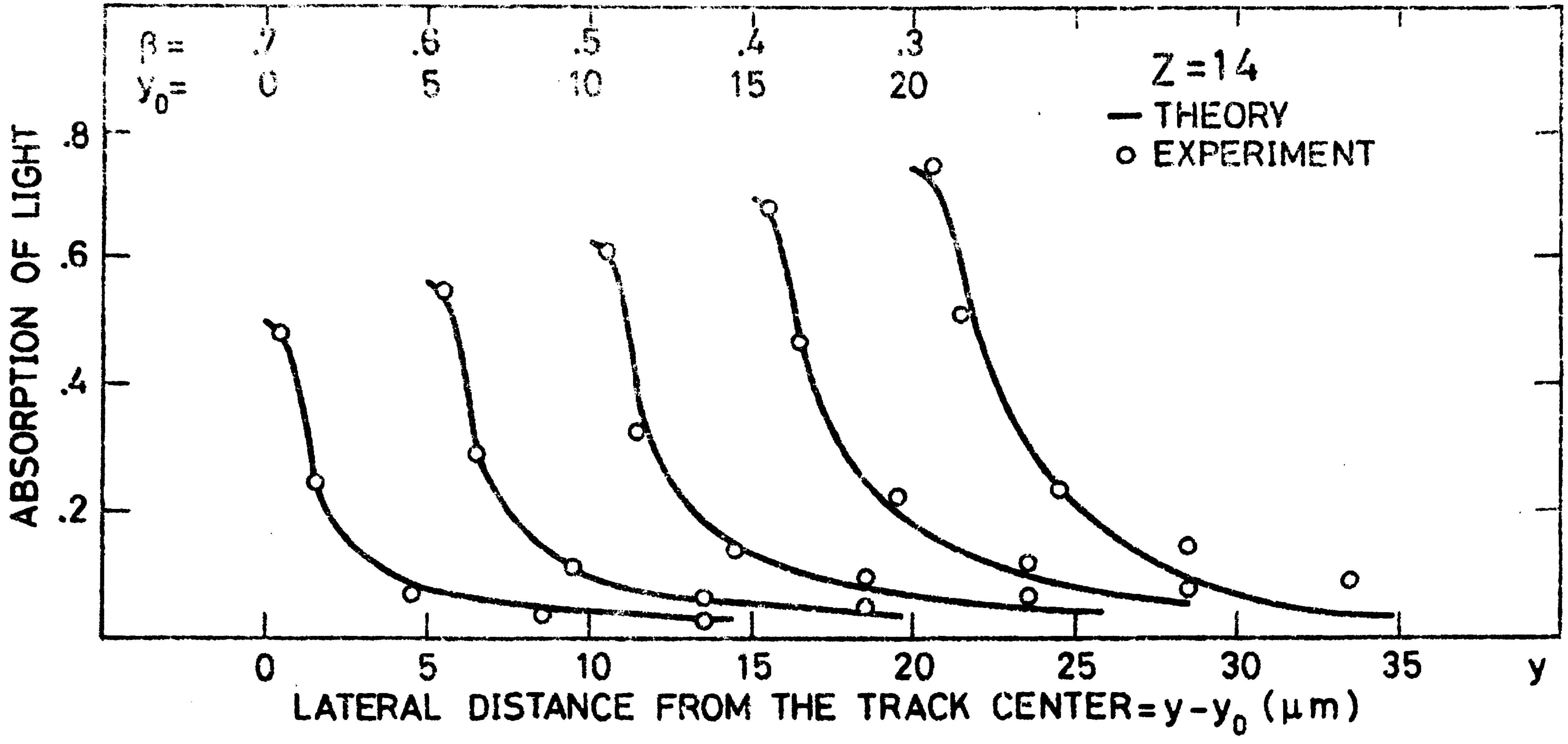
β = .7 .6 .5 .4 .3
y_0 = 0 5 10 15 20
Z = 14
THEORY
EXPERIMENT
ABSORPTION OF LIGHT
.8
.6
.4
.2
0
5
10
15
20
25
30
35
y
LATERAL DISTANCE FROM THE TRACK CENTER = $y - y_0$ (μm)

Fig. 4a

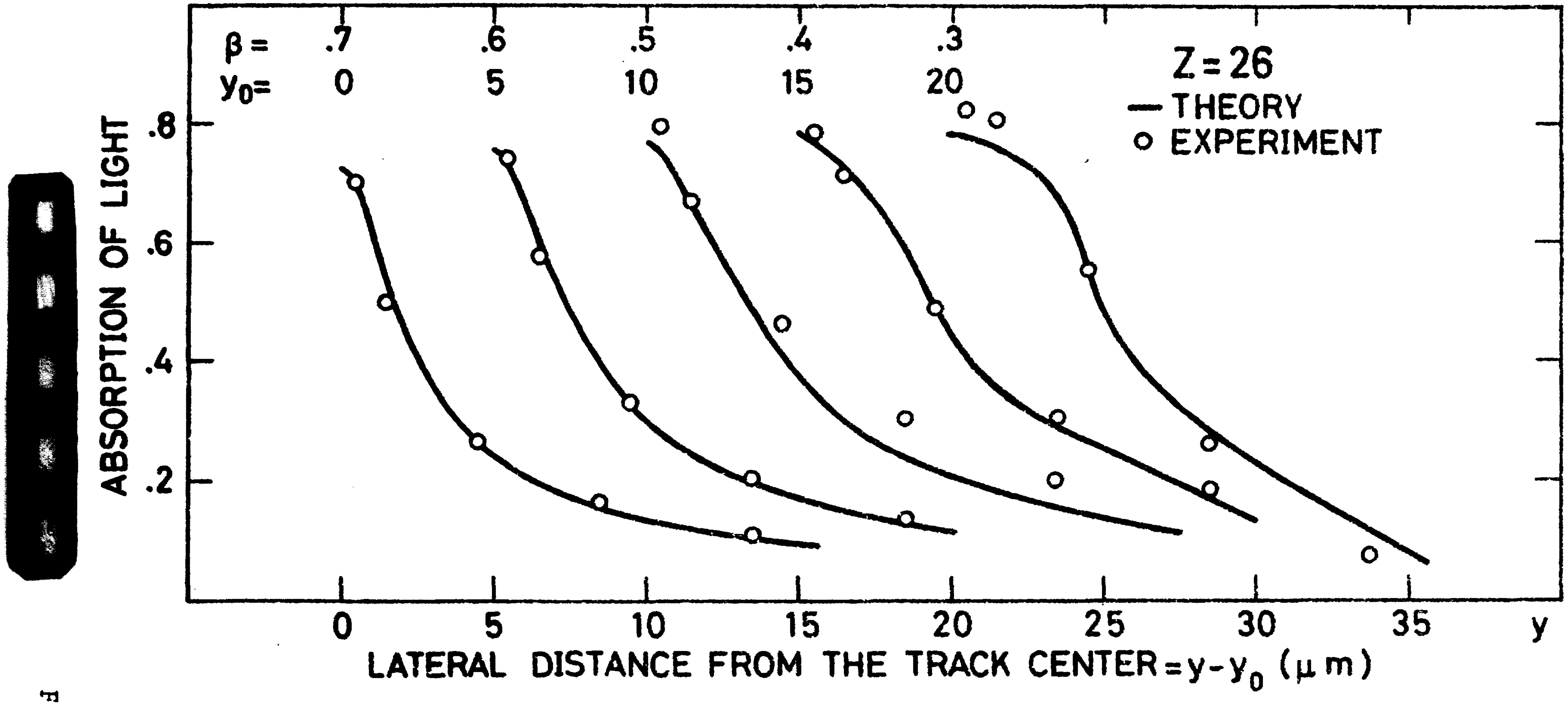
β = .7 .6 .5 .4 .3
y0 = 0 5 10 15 20
Z = 26
— THEORY
○ EXPERIMENT
ABSORPTION OF LIGHT
.8
.6
.4
.2
0
5
10
15
20
25
30
35
y
LATERAL DISTANCE FROM THE TRACK CENTER = y - y0 (μm)

Fig. 4b