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Cosmic Ray Physics Report

LUIP-CR-72-09

July 1972

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The relation between restricted energy loss and track width in nuclear emulsions.

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The restricted energy loss of charged particles is a useful parameter in the description of heavy ion tracks and in the calibration of mean track width measurements in nuclear emulsions.

A number of attempts have been made to relate the grain density of tracks in nuclear emulsions with parameters of ionization. A function based on the average energy loss, calculated from the Bethe-Bloch formula, fails to describe the grain density, especially in tracks of particles with high velocities (1-6). A different approach to the track formation theory is that of Katz and Kobetich (7), who base their theory on the energy dose deposited in the medium around the path of the ion. In this paper we will discuss a parameter of energy loss, which only considers energy transfers to secondary electrons up to a fixed maximum value. This parameter, which is called restricted energy loss (REL), differs from the Bethe-Bloch formula by the exclusion of a certain fraction of long delta rays. In track width measurements these long delta rays do not contribute to the measured quantity.

REL is given by the expression used by Barkas (6):

$$REL = \frac{2\pi \cdot n \cdot Z^2 \cdot e^4}{\beta^2 \cdot mc^2} \left\{ \ln \frac{2mc^2 \cdot \beta^2 \cdot \gamma^2 \cdot w_o}{I^2} - \beta^2 - 2C(\beta) \right\}$$

where n = the electron density in the emulsion,

m and e = the mass and charge of an electron,

$\gamma = (1 - \beta^2)^{-1/2}$

βc = the ion's velocity,

Z = the ion's effective charge for energy-loss,

I = the mean ionization potential of the atoms in the emulsion,

w_o = the chosen energy limit for secondary electrons,

$C(\beta)$ = a correction term which accounts for the density effect at high velocities and for the shell correction at low velocities.

The tracks of heavy ions in polymers have been discussed in terms of REL with some success by Benton et al. (8) and by Enge et al. (9), and in nuclear emulsions it has been shown that the REL is a useful parameter to describe the grain density of the tracks of lightly ionizing particles (2-5). The method of grain counting can not be used for particles with a rate of energy-loss exceeding a certain value, which depends on the emulsion sensitivity. Other estimates of the grain density in tracks of heavily ionizing particles can be based on photometric width measurements or measurements of the opacity of the tracks (10,11).

In this report we present relations between the photometrically determined mean trackwidths (MTW) and REL for tracks of heavy ions in nuclear emulsions. The measurements are made using a nuclear track photometer of a type earlier described by Jönsson et al. (10).

We have studied the track widths in two types of emulsion: Ilford G5, which registers all ionizing particles and Ilford K2, in which slow electrons produce tracks of only a few grains. The charges of the cosmic ray particles which produced the tracks have been determined in earlier investigations (12-15). The MTW data used in the present investigation has been taken from three other papers (15-17), in which the experimental details are also described.

The measurements in the G5 emulsion were made in two charge intervals, using different photometer slit widths. In Fig. 1 MTW values obtained with a slit width of 6.3 μm (in the emulsion plane) have been plotted against the restricted energy loss for particles with charges $4 \leq Z \leq 14$ and with energies in the interval 200 to 400 MeV/nucleon. Fig. 2 shows the corresponding relation for particles with charges $14 \leq Z \leq 26$ and with energies 100 to 800 MeV/nucleon using a slit width of 10.3 μm.

In the K2 emulsion, tracks of particles in the charge interval $4 \leq Z \leq 26$, with energies ranging from 40 to 220 MeV/nucleon, have been measured. The results are shown in Fig. 3. Here the slit width was 6.1 μm. The standard errors of the experimental points fall within the symbols in all graphs. The graphs show that within the errors of measurement there exists a one-to-one correspondance between REL and MTW.

The method of measurement means that the grain density is only registered within a certain volume around the track, the extension of which is determined by the dimensions of the photometer slit. In the calculation of REL, for a given track segment, the parameter w_o represents the maximum kinetic energy of those electrons (delta rays), which distribute their energy within the region covered by the slit. The chosen values of w_o for our measurements are given in the figure captions. A small variation in w_o does not change the shape of the MTW-REL relationship or affect the one-to-one correspondence between them.

It is not obvious which value to give to the parameter I, the mean ionization potential of the emulsion. In investigations using direct counts of the grains in the tracks of lightly ionizing particles it is assumed that only the energy that remains in the silver bromide crystals traversed by the particle can give rise to the latent image of the track. Accordingly, the REL is calculated only for silver bromide, and not for all the emulsion components. Hence, in this case I_{AgBr} = 450 eV. However, for solid tracks of heavily ionizing particles, a large fraction of the grain density is produced by delta rays which leave the particle path. For these tracks, it must be noted that some delta-rays originate from collisions in the gelatin. These delta-rays may enter silver bromide crystals near the particle's path and contribute to the track grain density. We therefore find it appropriate to treat the emulsion as a homogeneous medium, and the value I = 331 eV (mean value for standard emulsion) has been used in these calculations (6).

The investigations we consider here cover the velocity interval $0.3 \leq \beta \leq 0.8$. From the presented MTW data we conclude that, in the investigated intervals, within the errors of measurement, there exists a unique relationship between MTW and REL for a given slit width. For low velocities the relation between MTW and REL is not unique. No predictions for high velocities can be made on the basis of this investigation. However, in a limited velocity interval the REL parameter is a convenient tool for the description of the track width. A further conclusion is that the REL parameter can be used for the calibration of MTW measurements of tracks of heavy ions in nuclear emulsions.

We wish to thank Professor S. von Friesen and Professor K. Kristiansson for their interest and encouragement in this investigation.

The research reported in this document has been sponsored in part by the Swedish Atomic Research Council, which is gratefully acknowledged.

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Figure captions.

Fig. 1. Ilford G5 emulsion. Photometric mean track width (MTW) as a function of restricted energy loss (REL) in the charge interval $4 \leq Z \leq 14$. Kinetic energy $200 \leq E \leq 400$ MeV/n, slit width 6.3 μm and $w_o = 30$ keV. The parameters are discussed in the text.

Fig. 2. Ilford G5 emulsion. MTW as a function of REL in the charge interval $14 \leq Z \leq 26$. Kinetic energy $100 \leq E \leq 800$ MeV/n, slit width 10.3 μm and $w_o = 60$ keV.

Fig. 3. Ilford K2 emulsion. MTW as a function of REL in the charge interval $4 \leq Z \leq 26$. Kinetic energy $40 \leq E \leq 220$ MeV/n, slit width 6.1 μm and $w_o = 30$ keV.

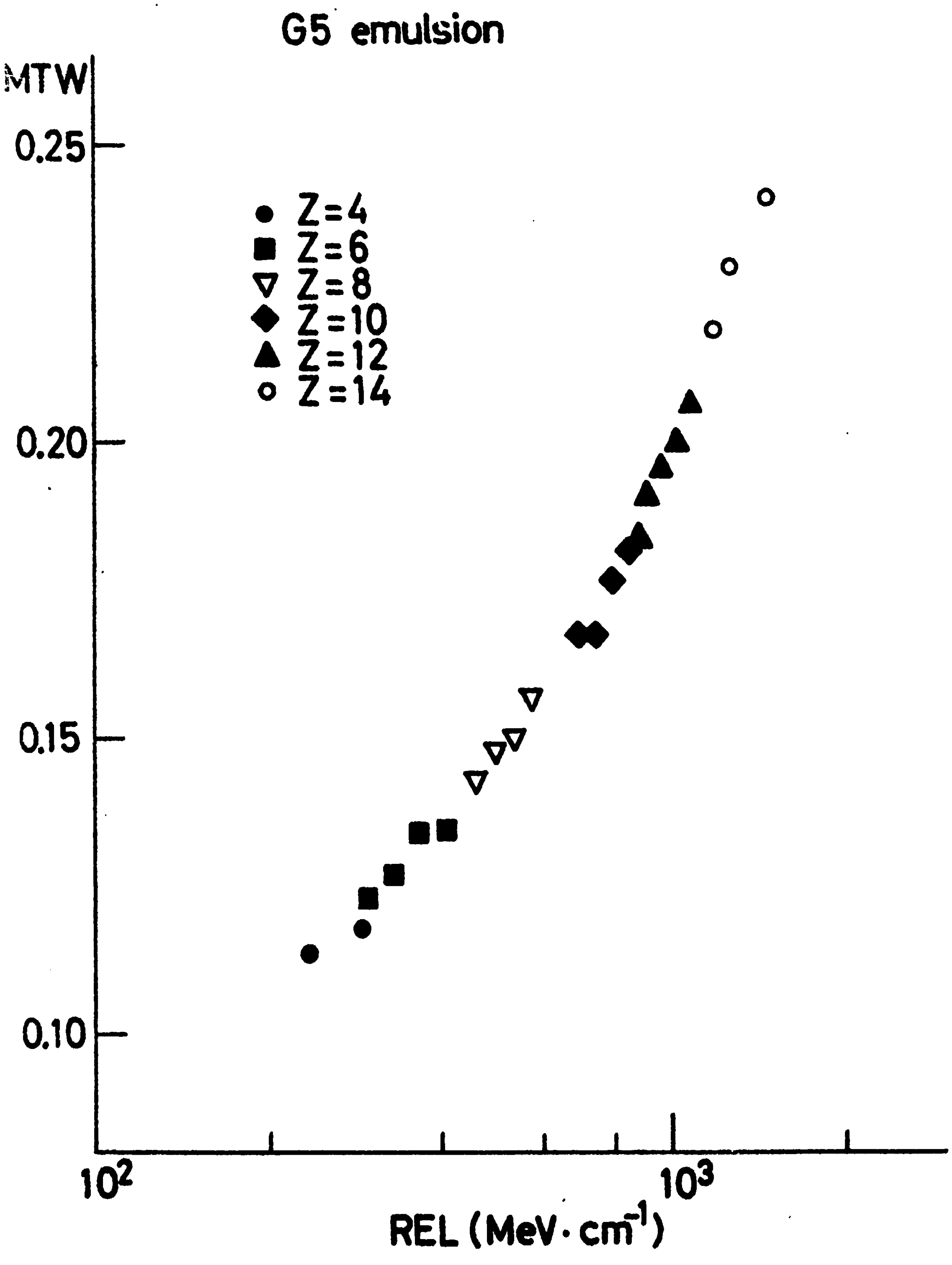
G5 emulsion
MTW
0.25
0.20
0.15
0.10
Z=4
Z=6
Z=8
Z=10
Z=12
Z=14
10^2
10^3
REL (MeV·cm⁻¹)

Fig. 1

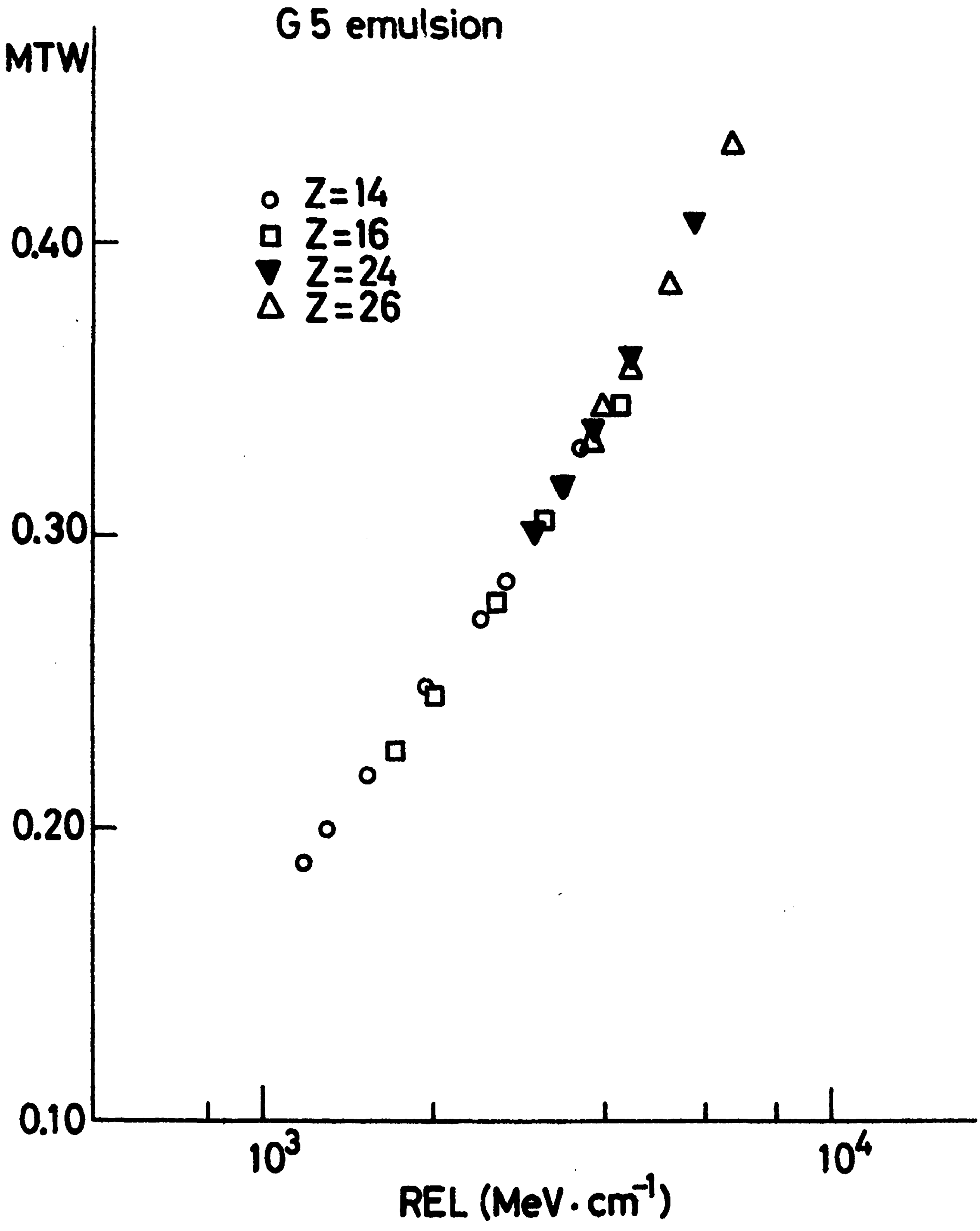
G 5 emulsion
MTW
Z=14
Z=16
Z=24
Z=26
0.40
0.30
0.20
0.10
10^3
10^4
REL (MeV · cm^{-1})

Fig. 2

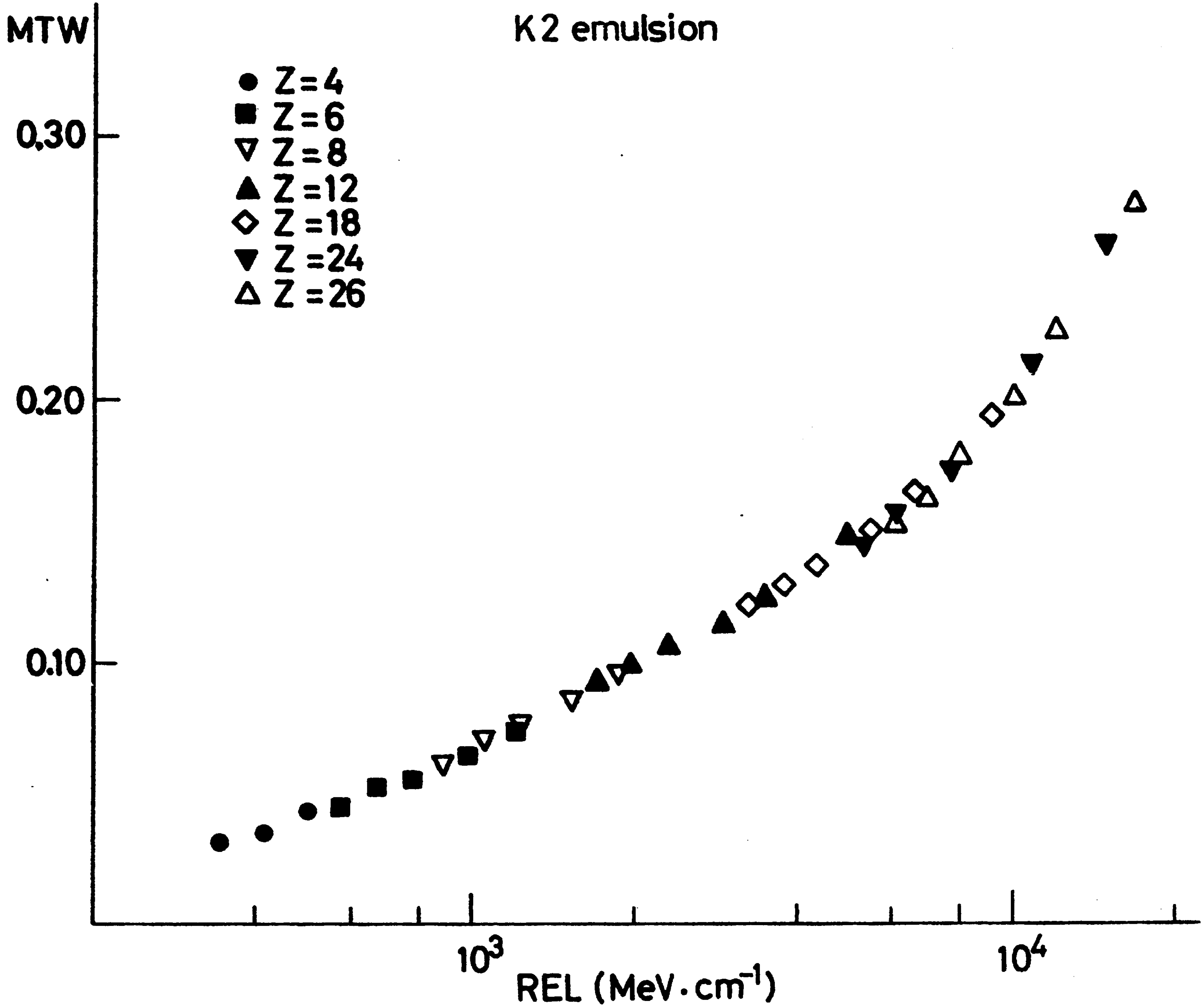
K2 emulsion
MTW
0,30
0,20
0.10
● Z=4
■ Z=6
▽ Z=8
▲ Z=12
◇ Z=18
▼ Z=24
△ Z=26
10^3
10^4
REL (MeV·cm^{-1})

Fig. 3