Cosmic Ray Physics Report

LUIP-CR-73-06

June 1973

AN EXPERIMENTAL STUDY OF THE FORMATION OF TRACKS OF FAST HEAVY IONS IN ILFORD G5 NUCLEAR EMULSIONS

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Submitted to the 13th International Conference on Cosmic Rays, Denver, Colorado, U.S.A., August 1973

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Transverse absorption profiles of tracks of heavy nuclei with charge numbers 14, 16, 20, 24 and 26 have been measured in Ilford G5 nuclear emulsions using a nuclear track photometer with a slit whose width reduced to the emulsion plane is 0.3 μm. The measurements cover the velocity interval $0.3 \leq \beta \leq 0.8$. The velocity is obtained from known values of the charge number and the residual range of the particle. The measured track profiles are compared with the track formation model by Katz and coworkers. According to our preliminary results reasonable agreement between experimental and calculated profiles can be obtained if the backscattered light is considered. The work is still in progress.

1. Introduction. In cosmic ray physics using nuclear emulsions as the particle detector the width of a track can be determined from measurements of the absorption of light by means of special track photometers. For calibration purposes it is of great importance to be able to predict the combined response of the photometer and the detector for ions of different charge number Z and velocity β. Such predictions must be based on a reliable track formation theory. Current ideas about track formation in nuclear emulsion emanate from the pioneering work by Bizzeti and Della Corte (1). These authors formulated a theory for the width of the very last portion of the track of a heavy ion. Their ideas have been modified and further developed by Katz and coworkers to obtain a theory which should be applicable to particles of all velocities (2,3). Up to now very few attempts have been made to compare this theory with experimental data (2-7). From this laboratory results have been reported only for ions with $6 \leq Z \leq 26$ at $\beta < 0.3$ by Rosander and Jacobsson (6) and for ions with $Z=26$ at $0.3 \leq \beta \leq 0.7$ by Mathiesen (7).

In the work by Rosander and Jacobsson (6) the widths of light absorption profiles were compared with Katz' theory for two different types of nuclear emulsions. The best fit was found for the less sensitive Ilford K2 emulsion. For the electron sensitive Ilford G5 emulsion the theoretical track widths could not be put into good accordance with the experimental track widths at half the profile maximum. A somewhat better agreement was obtained when they studied only the track core and used the profile width at 5/6 of the maximum.

In the report given by Mathiesen (7) a reasonable fit was obtained for underdeveloped Ilford G5 emulsions if a further parameter was incorporated into the theory. This parameter is thought to accomodate for changes in the observed transmittance of light caused by light backscattered into the cone of acceptance when using a photometer with a high numerical aperture. His work also shows that the fit of the calculated profiles depends on the assumed angular distribution of the delta rays. The assumption that all electrons are ejected perpendicularly to the ion's path yields better results than the distribution arising from collisions between the ion and initially free electrons at rest.

Considering the limited experimental checks of Katz' theory we have started a more comprehensive investigation. We have measured the transverse light absorption profiles on 27 tracks of particles with charge number $14 \leq Z \leq 26$ and velocity $0.3 \leq \beta \leq 0.8$. In this report we will present some preliminary comparisons of our experimental data with Katz' theory.

2. Experimental details and measurements. The detector used in this study consists of Ilford G5 emulsions and was exposed at Fort Churchill in 1967. The measured tracks of known residual range have been identified by Söderström et al. (8) and correspond to charge numbers 14, 16, 20, 24 and 26. The actual ion velocities were taken from the range-velocity calculations by Rosander and Larsson (9). All tracks used in this study fulfil the following criteria:

1. the tangent of the dip angle is less than 0.35
2. no readings must be taken closer to an edge than 8 mm

3. all readings must be taken in the depth interval between the upper 30 % and 55 % of the emulsion thickness.

With these conditions we intend to minimize systematic errors owing to dip, processing and light scattering. The photometric apparatus is described by Jacobsson et al. (10). In the present study we used a 53x oil immersion objective. The dimensions of the photometer slit correspond to 24.4 x 0.3 μm^2 in the emulsion plane. The tracks were adjusted parallel to the slit. During the readings the image of the track segments was moved perpendicularly across the slit. In each profile the transmission of light was measured at 1 μm intervals out to a lateral distance of about 85 μm to both sides of the track axis. The number of tracks of particles with different Z and β is shown in table 1. On each track with given Z and β four profiles were taken at approximately the same range. For numerical reasons all resulting data points, about 84,000 in number, could not be used in the com-

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

parison with the theory. The data were reduced and smoothened in the following way: All profiles taken at the same Z and β were lumped together and folded back at the track center. A smoothened transmittance profile was obtained by a least squares fit of a 5th degree polynomial in a double-logarithmic scale. From this fit transmittance values were calculated at six lateral distances, y = 0.5, 1.5, 4.5, 8.5, 13.5 and 39.5 μm. For each charge number the values at a given lateral distance were smoothened along β by fitting a cubic spline to the data. From this fit transmission values at given Z and y were extracted for β = 0.3, 0.4, 0.5, 0.6 and 0.7. 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.

3. Theory. The theoretical profile is calculated in three steps:
1. The density of grains at a given distance from the track axis is calculated according to the model given in (3). We have followed Mathiesen's algorithms (7) which differ from ref. (3) on a few points, a) the angular distribution of the delta rays is assumed to be $\cos\theta = 0$, i.e. it is simply assumed that the secondary electrons are emitted at right angles to the ion's path, b) the energy dissipation is calculated by the algorithm given by Kobetich and Katz (11) including the contribution of the straggling of the electrons, and c) all three terms are retained in Mott's formula which gives the energy distribution of the emitted delta rays.
2. The calculation of τ_p, the transmittance of parallel light through the emulsion follows closely the procedure given in (3).
3. A model for high aperture photometry is constructed by assuming that the observed absorption $1 - \tau$ can be found from a power series expansion in $1 - \tau_p$, the absorption of parallel light. Doing so the absorption can be written

$$1-\tau = a_o + a_1(1-\tau_p) + a_2(1-\tau_p)^2 + \dots\dots\dots\dots \quad (1)$$

In this part of the study two special cases have been considered:

Case 1: $a_o = 0$, $a_1 = 1$ $\qquad (a_i=0;\ i\geq 3)$
Case 2: $a_o = a_2 = 0$ $\qquad (a_i=0;\ i\geq 3)$

The theoretical profiles have been fitted to the experimental points by means of a parameter optimation algorithm. This is a procedure for solving the non-linear least squares problem. The quantity minimized by the procedure is the sum of the squares of the differences between the calculated and the experimental data. In the fit according to case 1 E_o, α and a_2 were treated as adjustable parameters. The quantity E_o is the characteristic dose for sensitization and development of 63 % of the emulsion grains in a uniform exposure. The quantity α is thought to accomodate for Rayleigh scattering in the emulsion in the forward direction, owing to the small dimensions of the grains. The negative constant a_2 is intended to account for the light reflected back into the cone of acceptance.

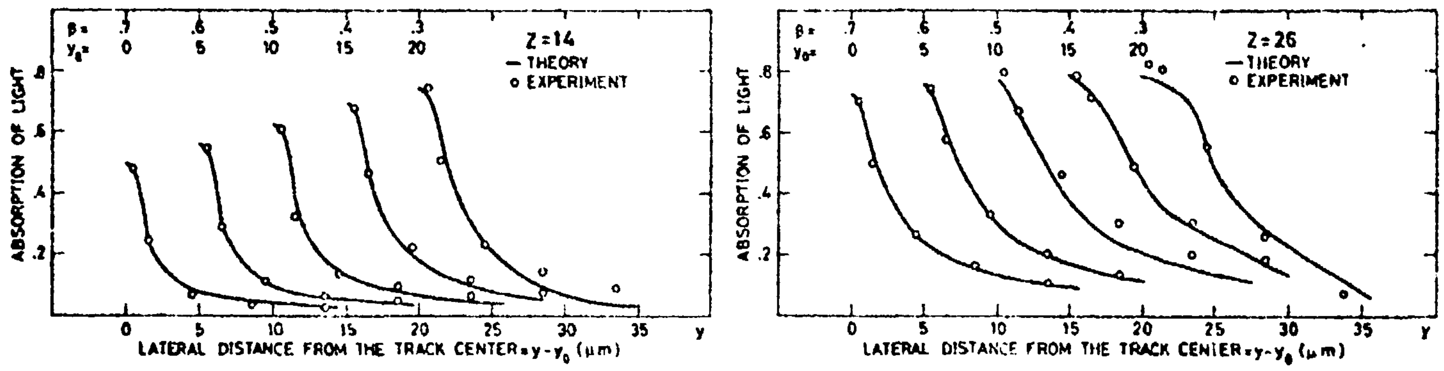

Fig.1-2. Comparison between calculated absorption profiles and experimental data. Theoretical curves for β=0.3 and 0.4 predicted from the fit for β=0.5 - 0.7.

4. Results and discussion. Fig. 1 and fig. 2 show the fitted profiles for case 1 together with the data points for Z=14 and 26. The fit has been made for β = 0.5, 0.6 and 0.7 for all Z values. The results obtained for the other charge numbers resemble closely those given for Z=14 and 26. The values obtained for the constants were E_0 = 6.8 keV μm^{-3}, α = 0.06 and a_2 = - 0.22. As an application of the model the absorption profiles for β = 0.3 and 0.4 were predicted. A reasonable fit is obtained also for these velocities, in spite of the fact that the track structure begins to change more rapidly when β approaches these low values.

Since the numerical values of E_0 and α are interdependent,we have also tried to determine E_0 experimentally. The value of E_0 was estimated according to the method described in (3). The value of E_0 was found to be 10.5 keV μm^{-3}. With this value of E_0 a new fit was made to all 150 data points which yielded the values α = 0.09 and a_2 = - 0.22. No obvious changes in the calculated profiles as compared with the previous fit could be found.

The values E_0 = 10.5 keV μm^{-3} and α = 0.09 were used in a fit of the transmission profiles according to case 2. Here a_1 was treated as an adjustable constant. This fit gave a sum of squares 65 % higher than that obtained for case 1. Our conclusion is that the model based on case 1 is more realistic.

The work reported here will continue. We believe that the large amount of experimental data available to us will make it possible to improve our calculations of the combined response of the photometer and nuclear emulsion to ions of different charge number and velocity. In the first place we plan to use more complex models to describe the backscattering of the reflected light. However, we are of the opinion that the remaining differences between theoretical and experimental profiles are mainly due to the approximations inherent in the calculation of the spatial distribution of the energy delivered to emulsion grains. Although some improvement can be expected from the use of a more realistic form for the angular distribution of the emitted electrons, we feel that improvements in the theory of electron energy dissipation are needed to bring the calculated profiles into closer agreement with observations.

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