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Dependence of the Taper Length of Emulsion Tracks on Particle Charge

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Proceeding from Freier's hypothesis that the tapering of tracks is due to the increase of specific energy losses, it is suggested that an increase of the quantum yield of developed grains with increasing energy absorbed by the photographic layer takes place in nuclear as well as in x-ray emulsions. The energies at which this phenomenon begins are approximately the same. The dependence of the taper length on the particle charge has been computed. The calculations satisfactorily agree with the available experimental data.

IN the past few years, a method has been devised which enables us to identify, by the length of the taper part of the track, the charge of the multiply-charged particles of the heavy component of the primary cosmic radiation which stopped in the emulsion.

Protons and α-particles are relatively easily identified by the grain density in the track, because the tracks of these particles are developed in the film in the form of a discrete chain of grains. The tracks of multiply-charged particles are in the form of a continuous colony of grains, the counting of which is practically impossible. One can, however, utilize another property of such particles: the track of these particles thins down appreciably towards its end. The utilization of the taper length for the determination of the charge has been first considered in the work of Freier[1] who gave a qualitative relationship. It was assumed there that the thinning down is due to the decrease of the specific losses because of electron capture by the ionized nucleus while it is slowing down. The probability of capture or loss of an orbital electron is determined by the velocity of the particle and depends also on the number of already captured electrons; the thinning down becomes noticeable after the capture of the first k-electron.

The experimental taper lengths obtained later[2] do not agree with the theoretical calculations. In addition to some inaccuracy in the calculation pointed out by Perkins[3], a more serious argument against the working hypothesis of the calculation is, according to Lonchamp[4], the discrepancy between the calculated and experimental energy of the residual paths of the particle.

New data became recently available, on the basis of which one can carry out a more exact calculation of the taper length, depending on the particle charge. One can also make some remarks about the mechanism of the thinning down.

It is known that during transition through matter, charged particles spend a substantial part of their energy on the ionization of the matter atoms. The energy losses are determined by the following relations[5]:

$$-dE/dx = (4\pi Z^2 e^4 / mv^2) N_A Z_A \ln (2mv^2 / I_A), \qquad (1)$$

where m is the electronic mass, v – the velocity of the particle, I_A – the mean ionization potential for the atoms of the matter, N_A and Z_A – the number of atoms per cm^3 and the atomic number of the atoms with mass number A, and Z the charge of the impinging particle. This formula is obtained in the Born approximation, by averaging over all the ionization potentials (when the velocity of the particle is greater than that of the orbital electrons and also for matter having a not too large atomic number).

If the velocity of the particle is of the order of the velocity v_e of the orbital electrons, then the dependence of the charge of the particle on its velocity starts to appear. Then one should write [in Eq. (1)] $Z = Z_{\text{eff}}(v_e)$. For the investigation of this dependence, let us use the Thomas-Fermi method[6,7]. In the calculations below, the Thomas-Fermi method is used only up to the K-shell. For the K-shell, we use formulas derived on a quantum-mechanical basis:

$$mv_e^2/2 \approx 13.5\, Z_{\text{eff}}^{4/3}\,(\text{eV}); \quad 1 \leqslant Z_{\text{eff}} \leqslant (Z-2), \qquad (2a)$$

$$mv_e^2/2 = 13.5\, Z_{\text{eff}}^2\,(\text{eV}); \qquad (2b)$$

$$(Z-2) \leqslant Z_{\text{eff}} \leqslant Z.$$

As mentioned above, Eq. (1) is obtained after summing over all the electrons of the atoms in the matter. In the transition of charged particles through matter with high atomic number, not all the electrons contribute to the slowing down, but only a part proportional to $Z_A^{1/3} v_s \hbar / e^2$, where v_s is the velocity of the orbital electrons of the matter. Taking this into account, Eq. (1) will take the form[8]

$$-\frac{dE}{ax} = \frac{4\pi Z_{eff}^2 e^4 \gamma^2}{m v_e^2} N_A Z_A^{1/3}$$
$$\times \frac{v_e}{\gamma v_0}\left[3\left(\frac{v_e}{2Z_{eff}\gamma v_0}\right)^{1/3} - \frac{v_e}{2Z_{eff}\gamma v_0}\right], \qquad (3)$$

where $v_0 = e^2/\hbar$; $v_e = \gamma v$. We will call taper length L the length of the residual path, from the point where the velocity of the ion is of the order of the velocity of the orbital K-electron, to the end of the path:

$$L = -\int_{v=0}^{v=v_e Z/\gamma} dx \qquad (4)$$
$$= \int_0^{E_{CI}} \frac{dx}{dE} dE = \int_{Z_0}^{Z} \frac{dE_{CI}}{dZ_{eff}}\left(\frac{dx}{dE}\right) dZ_{eff}$$

where γ is a coefficient expressing the relationship between the velocity of the orbital electrons and the velocity for which the electron capture is most probable; $mv_e^2/2$ is determined by Eq. (2a) and (2b); Z_0 is determined from the expression (3) when $dE/dx \approx 0$, taking (2a) into account; a is the mass number of the impinging particle;

$$E_{CI} = \left(\frac{Mav^2}{2}\right)_{v=v_e/\gamma} = 1836\, a \frac{mv_e^2}{2}\frac{1}{\gamma^2}.$$

Substituting (3) and the expression of E_{cr} [(using (2a) and (2b)] into (4), we get the following relation for the taper length:

$$L = k \frac{0.11\, a}{\gamma^3 \rho (Z_A^{1/3}/A)_{av}}$$
$$\times [1 + 0.33 \ln (Z-2)]\, 10^{-4} \text{ (cm)},$$

where ρ is the emulsion density; the subscript $_{av}$ means averaging over all the emulsion atoms; k is a coefficient taking into account the approximate character of the relationship (3).

For a photoemulsion, $\rho (Z_A^{1/3}/A)_{av} \approx 0.17$; substituting this value (and letting $k \approx 1$; $a \approx 2Z$; $\gamma = 0.65$[9,10]), we get

$$L \approx 4.7\, Z[1 + 0.33 \ln (Z-2)] \qquad (5)$$

(in microns). This formula is good, generally speaking, for $Z > 2$, which is indicated by the presence of the logarithmic term which appears because of electrons above the K-shell (for $Z = 2$, the second term of (5) should be deleted).

Taper lengths computed from Eq. (5) will be somewhat underestimated for large Z's because in this case $a > 2Z$.

The results of the calculations from formula (5) are presented in the Table and can be compared with the calculations by Freier (from the formula $L \approx 0.72Z^2$ for $Z < 9$) and with the experimental data. The data for $Z = 2$ is taken from Ref. 11; it follows that the charge of the helium ion is unstable at an energy of 2.5 mev (corresponding to the 8.4μ path in the photoemulsion). For $Z = 3$, the data are taken from Ref. 10 (measurements on $_3Li^8$). The calculation is however carried out for $a = 2Z$, and it is therefore necessary to recompute the taper length for $a = 8$, which gives 19.6μ. For $Z = 6$, the data are taken from Ref. 12 – (artificial acceleration of carbon nuclei). The remaining data are taken from Ref. 2.

The taper length computed from formula (5) is in better agreement with the experimental data than the result of Freier's calculations.

The above calculations are carried out with the assumption (the same as Freier's) that the width of the track is determined by the magnitude of the specific energy losses. An experimental confirmation of this point of view is given in Ref. 13, where it is shown that the width of the track of multiply-charged particles from the heavy component of a cosmic radiation is proportional to the specific energy losses up to relativistic energies, if these losses do not exceed 50-60 kev/μ in the emulsion.

In addition, if the dimensions of the developed grains do not depend on the specific energy losses after the mentioned limit, then the external increase of the grain density with the rise of the specific energy losses reminds the effect of change in quantum occurrence of developed grains with the rise of the energy of the quanta, in an x-rays emulsion. (By quantum occurrence, we mean the number of emulsion grains which have gotten the possibility to be developed, per absorbed quantum). It follows from Ref. 14, that the quantum occurence is unity in the range of wavelengths from 1.5 to 0.3 A, and is proportional to the energy of the quanta if the wavelength is decreased from 0.3 to 0.01 A.

It follows from the comparison of specific losses with the energy of the radiation quantum that, in nuclear emulsions, the proportionality of the track's width to the specific energy losses starts to appear starting from somewhat larger magnitudes

TABLE

Dependence of the taper length on the particle charge

Z	Taper length (in microns) Experimental data.	According to Freier	Using formula 5
2	8.4	3	9.4
3	19	6	14.7 (19.6 for $a=8$)
6	50	18	41
9	75	48—58	70
10	90	48—66	80
12	130	64—88	100
13	140	66—114	110
14	130	78—130	121
16	160	100—160	141
20	190	145—240	184
25	240	250—340	241

than in the x-ray emulsions. The rise of the number of developed grains is , in the latter case, due to the secondary electrons. The same mechanism determines apparently the thickening of the multiple charge particle tracks.

The discrepancy between the theoretical and the experimental taper lengths led Perkins[3], and later Lonchamp[4] , to the assumption that the thickening of the particle track is due to δ-electrons. It is known that the number of δ-electrons increases with the decrease of the particle energy, and that the energy decreases – hence their path is shortened. The capture of orbital electrons by a nucleus starts for particle velocities of the order of 10^9 cm/sec; therefore, the maximum electron energy, determined by the relation $w_{max} = 2mv^2$ (where w and m are the energy and mass of the electron and v – the velocity of the particle), is equal to 11 ev.

The paths of electrons with such a small energy have been poorly investigated and although one can determine their number for a given interval of energy, a quantitative estimation of their influence on the track's width is difficult.

In order to check the assumption that the taper length is determined by the increase in the specific energy losses by capture of orbital electrons, one has to measure the change in the specific energy losses for multiply-charged particles. Kuznetsov, Perfilov and Lukirskii[10] have measured the specific energy losses of Lithium ions from explosive nuclear fission, on the basis of the linear dependence of the specific energy losses on the darkening. They show that the specific energy losses almost do not change when the charge of the particle is decreased. This result is confirmed by the experiment with artificially accelerated nitrogen ions[15]. Let us note that the nitrogen ion energy was not sufficient for a total ionization, i.e., the measurement was carried out only in a taper region where the ionic charge was known to be less than seven. Therefore, on this basis one cannot reach the conclusion of independence of the specific energy losses on the energy for nitrogen nuclei, i.e., for nitrogen atoms with charge seven.

After what was said, it is obvious that the difficulty of the taper length measurement for particles with $Z < 6$ does not come from the fact that the length is small, but from the fact that specific energy losses vary negligibly with the electron capture by the slowing down particle, and that the width of the track is practically constant, i.e., there is no visible taper. Further experiments with artificially accelerated multiple charge ions of sufficient energy losses on the width of the particle track.

1 Freier, Lofgren, Ney and Oppenheimer, Phys. Rev. **74**, 1818 (1948).
2 Hoang-Tchang-Fong and D. Mortellet, Compte rendus **231**, 695 (1950).
3 D. H. Perkins, Proc. Roy. Soc. (London) **203**, 399 (1950).
4 S. P. Lonchamp, J. Phys. Rad. **14**, 433 (1953).
5 N. Bohr, Phys. Rev. **58**, 654 (1940); **59**, 270 (1941).
6 J. Knipp and E. Teller, Phys. Rev. **59**, 695 (1941).
7 N. Mott and G. Massey, *Theory of atomic collisions*.
8 N. Bohr, *Transition of charged particles through matter*.
9 K. C. Stephens and D. Walker, Phil. Mag. **45**, 543 (1954).
10 Kusnetsov, Likurskii and Perfilov, **100**, 665 (1955).
11 P. L. Kapitza, Proc. Roy. Soc. **106**, 602 (1924).
12 J. F. Miller, Phys. Rev. **83**, 1261 (1951).
13 M. Ceccarelli and G. T. Zorn, Phil. Mag. **43**, 356 (1952).
14 D. Bramley and R. H. Herz, Proc. Phys. Soc. **638**, 90 (1950).
15 Reynolds, Scott and Zucker, Phys. Rev. **95**, 671 (1954).

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