On the Nature of the Cone-like Shape of Tracks of Multi-charged Ions in Nuclear Emulsions

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Photometric investigations of the tracks of multi-charged particles in fine grained nuclear emulsions of various sensitivity indicate that the thinning down of the track near the end of the range is not due to variation of the total specific energy losses but to variation of the energy spent by δ-electrons with $E \geq 2$ kev near the track axis. A new method for measuring the total charge of multi-charged particles in fine grained nuclear emulsions is described.

1. INTRODUCTION

THE tracks of multiply-charged ions in nuclear emulsion of medium and high sensitivity have the peculiarity of a thinning down at the end of the ion path. Beginning with the work of Freier[1], this thinning down was connected by many investigators[2-5] with a decrease of the specific ionization energy loss dE/dx at the end of the ion path because of electron pickup. The thinning-down length was understood to mean the average path length after which a fragment of initial charge Z_0 captured its first orbital electron. This led to the method of determining Z_0 from the thinning down length of the track. However, the decrease of dE/dx in the capture of an electron by the ion is not as it would seem from first examination since at the same time as the charge is decreased the velocity of the ion is decreased, and $dE'/dx \sim Z^2_{\text{eff}}/v^2$. Therefore there is doubt that a particular thinning-down length exists, especially since the actual thinning down (because of change of dE/dx), if it does exist, can easily be masked by changes of the track half width which are caused by the δ-electrons.

In the past few years Güer and Lonchamp[6-8] developed new ideas about the mechanism responsible for changes of track thickness in nuclear emulsion. The thinning down is explained primarily by changes in the space density of δ-electrons and not only by changes in the specific ionization loss. Confirmation of this point of view comes from the results of Ref. 9 on measurements of specific ionization loss of nitrogen isotopes in emulsion.

2. EXPERIMENTAL PART

In order to describe the relative shares of changes in specific ionization along the path length and the spatial distribution of δ-electrons causing the thinning down of the track at its end, it is essential to have a method of separating both these effects. This was attained by using emulsions strongly different in sensitivity.

For the investigation, fine grained nuclear emulsions type P-9 prepared in the laboratory of N. A. Perfilov were used. If the sensitivity of an emulsion is characterized by specific ionization dE/dx for particles causing a visible track, then the emulsion P-9_0 had a minimum value of dE/dx near 50 kev/μ, while for the emulsion P-9_s– approximately 4.5 kev/μ. The plates were exposed to completely ionized nitrogen atoms with an energy of 90 mev at an angle of 10° at the surface of the emulsion. After development the nuclear tracks were studied with the aid of a photometric installation. The dependence of the track darkening $(I_\varphi - I_c)/I_\varphi$ in an interval of 5μ on the remaining ion path length in the emulsion was measured. The slit size in the objective plane was $(0.8 \times 5)\ \mu^2$.

3. RESULTS OF THE MEASUREMENTS AND DISCUSSION

The observed dependence of darkening on path length for the N^{14} ion is given in Fig. 1. The appearance of N^{14} ion tracks in emulsions of different sensitivities is seen in the microphotographs of Fig. 2.

As can be easily seen from the curves of Fig. 1, the thinning down of the N^{14} ion tracks is clearly shown for the sensitive emulsions, but does not appear for the insensitive emulsions. Since in the low sensitivity emulsion (P-9_0) the N^{14} ion forms a track consisting of separate grains, the entire darkening characterizes the specific ionization loss dE/dx of the nitrogen ion along its path. In agreement with the results of Ref. 9 we can conclude from curve A that the energy loss of a nitrogen ion along its path changes insignificantly and can not be the cause of the observed changes of darkening of tracks in more sensitive emulsions (P-9_s).

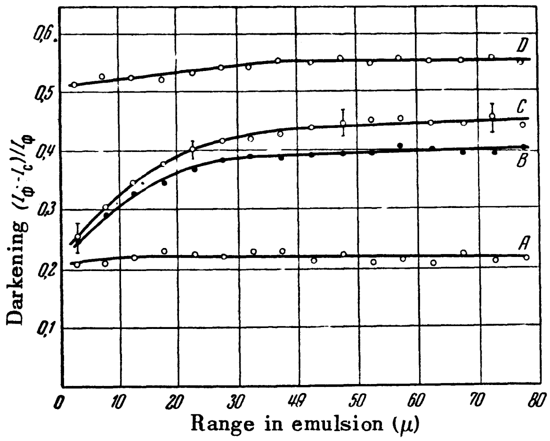

FIG. 1. Dependence of total darkening in a N^{14} ion track, on range. A – Low sensitivity emulsion (P-9_0); B and C – sensitive emulsions of two different batches (P-9_s); D – Ilford E-1 emulsion.

The indicated peculiarities of multiply charged ions in sensitive and insensitive emulsions can be understood if we assume that the thinning down of the tracks is caused not by the full dE/dx energy loss of the particle, but only by a small part of the total collision losses which cause the appearance of δ-electrons with energy more than a certain E_{min}. In the sensitive emulsion these δ-electrons cause an additional broadening of the track which decreases as the ion speed de-

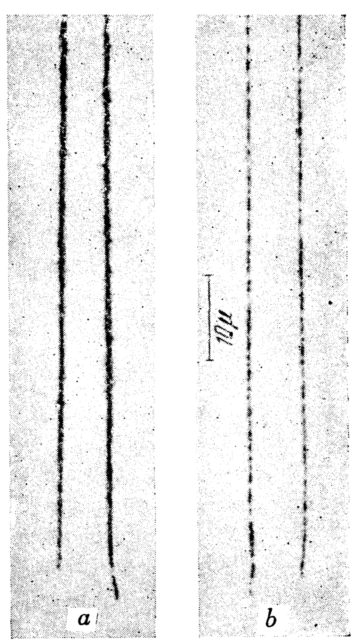

FIG. 2. Microphotographs of N^{14} tracks. a – in sensitive emulsion b – in low sensitivity emulsion.

creases because of the lesser δ-electron energy. In the insensitive emulsion these δ-electrons do not give any observable photographic effect.

To further examine this viewpoint we have calculated the dependence of the energy of the emitted δ-electrons near the track axis on the remaining range of the particle for the ions N^{14}, B^8, Li^8. The energy emitted by δ-electrons in 1μ of path for a multiply charged particle in emulsion of normal composition is determined by the equation:

$$K_\delta = 2.33 \cdot 10^{19} \cdot \frac{Z_{eff}^2}{v^2} \ln \frac{E_{max}}{E_{min}} \text{ kev}/\mu,$$

where v is the particle speed, Z_{eff} is the particle charge at the given speed, $E_{max} = 2mv^2$ is the maximum energy of the δ-electrons, E_{min} is the minimum energy of the δ-electrons which can cause track broadening. The dependence of the charge of the particle on speed has been taken from Refs. 10 and 11. The dependence of speed on range was determined from Ref. 12 for Li^8 and B^8, and from Ref. 9 for N^{14}.

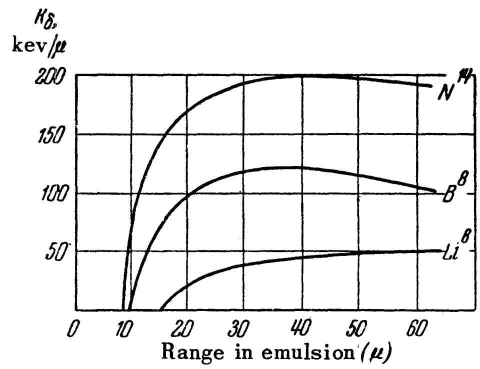

FIG. 3. Dependence on the range of energy lost as δ-electrons of energy ≥ 2 kev in the vicinity of the axis of a multiply charged particle track for ions N^{14}, B^8 and Li^8.

Taking into account the results of Demers[13], with fine grained emulsions where it was shown that δ-electrons with $E = 2$ kev are capable of sometimes causing development of a single grain near the track, it is reasonable to take 2 kev as the minimum δ-electron energy capable of broadening the track. Calculations of the dependence of K_δ on the range under this assumption is given in Fig. 3. In Fig. 4, we present the results of photometric analysis of Li^8, B^8 and N^{14} tracks in emulsion P-9_s. From a comparison of Figs. 3 and 4 the qualitative dependence of $(I_\varphi - I_c)/I_\varphi$

and K_δ on range for ions of various charge is seen. One difference is that within the limits of the examined ranges K_δ goes through a maximum, whereas the full darkening (or the track half width) continues to increase. This circumstance is undoubtedly connected with the increased percentage of high range δ-electrons with increase of particle velocity. An exact calculation of the influence of the δ-electrons on the characteristics of the track involves knowledge of the range energy relation for electrons in emulsion. The above mentioned experimental results and calculations allow definite conclusions to be drawn about the cone formations of multiply charged particles in emulsion. The thinning down of the tracks of multiply charged ions at the end of their range is determined by the change in energy lost to δ-electrons with energy $> E_{min}$ in the vicinity of the track axis, and also on their energy distribution. The E_{min} used here, the minimum δ-electron energy capable of broadening the track, is determined not only by the emulsion sensitivity, but by the size of the developed silver grains in the emulsion. The larger the developed grains, the larger must the δ-electron energy be in order to cause a photo reaction in a micro crystal of AgBr near the trajectory of the multiply charged particle, but beyond normally developed silver grain. From this point of view, it is clear why emulsions of similar sensitivity (P-9_s and Ilford E-1), but of different grain size, show different degrees of track thinning for N^{14} near the end of path (Fig. 1). The discrimination of fine grain emulsions for multiply charged particles is clearly seen.

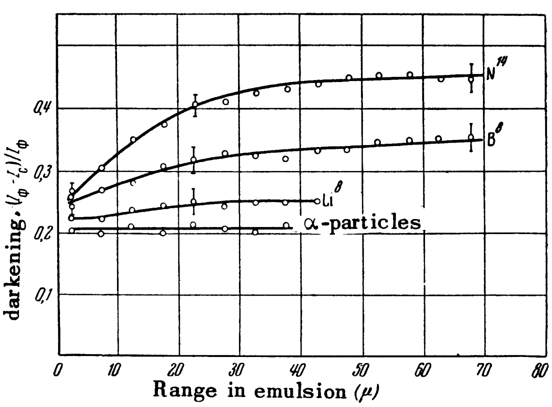

FIG. 4. Total darkening as a function of range for N^{14}, B^8 and Li^8 in P-9_s emulsion ,

The influence of the δ-electrons (with energy greater than E_{min}) can also be used to explain the observation that in fine grain emulsion there is a noticeable difference in darkening in tracks and heavy fission fragments of uranium at the beginning of their path[14,15]. The darkening caused by a light fragment is on the average 15-20% greater than that caused by a heavy fragment[16]. In Ref. 15, Mathieu and Demers conclude from the observed difference in darkening that the light fragment has a higher specific ionization loss at the beginning of its track than the heavy fragment (11.6 and 9.4 mev/μ, respectively). This conclusion is in contradiction with other experimental data and with theory, as the authors themselves note. These difficulties disappear if the assumption is made that the difference in darkening is not due to difference in dE/dx, but rather to a different energy distribution of δ-electrons for the light and heavy fragment. If we calculate the maximum δ-electron energy at the beginning of the track for the light and heavy fragment, we get respectively 2.2 and 1.0 kev. Thus the energy loss to electrons of energy greater than 1 kev in the vicinity of the track axis will be an important quantity for the light fragment, and negligible for the heavy fragment. The result will be a broadening of the light particle track at its beginning. The specific ionization losses for the light fragment will be smaller than for the heavy fragment.

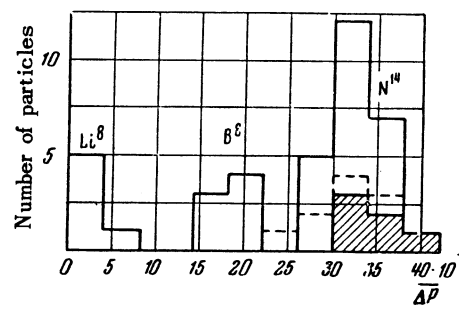

FIG. 5. Distribution of $\overline{\Delta P}$ for particles of various charge, N^{14}, B^8, Li^8. ($\overline{\Delta P}$ – the average change in darkening $(I_\phi - I_c)/I_\phi = P(R)$ in the last 25 μ of track).

Thus the characteristics of multiply charged particle tracks in sensitive emulsion make it difficult, if not impossible, to measure the specific ionization loss without taking into account the secondary ionization caused by fast δ-electrons.

4. METHOD OF CHARGE DETERMINATION

In the course of this investigation, a new method of determining the charge of a multiply charged particle from the characteristics of its last 25μ of track was evolved. Since the thinning down of a track at its end is determined by the number and energy distribution of the δ-electrons, which in turn are determined by the type of ion, it is clear that the relationship between track characteristics and particle charge can be found. Calculation of this dependence with sufficient accuracy is impossible at the present time, although an empirical relationship using particles of known charge can be found. It is essential to note that the proposed method is most effective with fine grained emulsions (grain size of AgBr $0.06\,\mu$) since we then have a close approximation of the dependence of the full darkening $(I_\varphi - I_c)/I_\varphi$ on range to the function $K_\delta = f(R_{\mathrm{rem}})$, for small remaining range.

Charge determination can be made as follows. Using photometric analysis of a multiply-charged particle track, the dependence of darkening $(I_\varphi - I_c)/I_\varphi = P(R_{\mathrm{rem}})$ on range is determined for the last 25μ of track. This dependence is characterized by some average change in darkening $\overline{\Delta P}$ between adjacent scanning fields. The average change in darkening was calculated from the average change in slope of the $P(R_{\mathrm{rem}})$ curve, $\overline{\Delta P} = A \tan \overline{\varphi}$, where $\overline{\varphi} = \frac{1}{n}\sum_{i=1}^{n} \arctan(\Delta P_i / A)$ the average angle, ΔP_i is the change in darkening for adjacent regions, A is the ratio of the scales used for $P(R_{\mathrm{rem}})$ and R, $(n+1)$ is the number of regions measured in the 25μ. In our measurements the scanning slit was 5μ long in the objective plane, so that $n = 4$. The absolute charge is then determined from a smooth curve relating average darkening change $\overline{\Delta P}$ to particle charge. This curve is constructed for particles of known charge.

This method has the following properties, which are also seen from the experimental results presented below: 1) the possibility of limiting observations to a small region near the end of the particle track which is made possible by the strong dependence of the particle charge on the slope of the curve $(I_\varphi - I_c)/I_\varphi = P(R_{\mathrm{rem}})$ just near the end of the particle range; 2) the weak dependence of ΔP on the angle of the particle track in the emulsion allows charge measurement on tracks entering at angles up to 30° without corrections; 3) the weak dependence of ΔP on small variations of emulsion sensitivity and development allow the use of a single calibration curve for emulsions of different batches and different experiments.

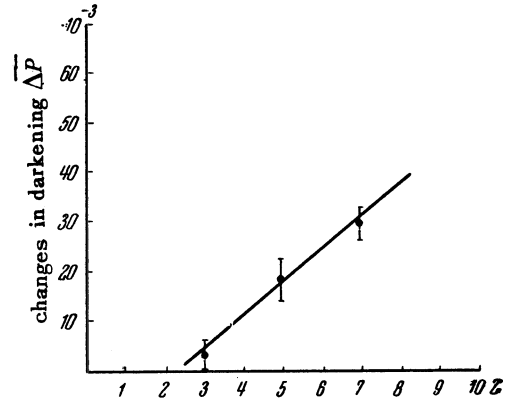

FIG. 6. Dependence of $\overline{\Delta P}$ on ion charge Z.

Figures 5 and 6 show some results typical of the described method. Figure 5 shows the distribution of ΔP for particles of various charge (N^{14}, B^8, Li^8); for the N^{14} ion results are also shown for tracks entering at 15° to the emulsion (lined section) and for less sensitive emulsion (dotted line). Figure 6 shows the dependence of ΔP on particle charge for P-9_s emulsion, Good discrimination of charge is seen from the curve, at least up to a $Z = 10$.

The accuracy of charge measurement by this method evaluated by measurements of N^{14} tracks is about 0.8 units of charge. It must however be pointed out that the charge measurement by the above method is influenced by the particle mass. If we take into account the various possible isotopes of the measured ions with mass differences up to 20 or 30%, this will lead to variations of like magnitude in residual range at a given velocity, and will lead to an error of about 0.5 units of charge. Thus the probable error in determining the charge of an unknown multiply charged particle is not higher than ± 1.3 units of charge.

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