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Abstract

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ON A QUANTITATIVE TREATMENT OF THE PROCESS OF FORMATION OF A LATENT PHOTOGRAPHIC IMAGE BY IONIZING PARTICLES

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A. P. Zhdanov [1], using an analogy with the problem of the free path of molecules, showed that the density ν of the track of an ionizing particle in a photographic layer is given by the formula

$$\nu = \frac{C_{\text{vol}}}{\pi d^3/6} \cdot \frac{\pi d^2}{4} = \frac{3C_{\text{vol}}}{2d} \tag{1}$$

(C_{vol} is the volume concentration of AgHal in the emulsion; d is the diameter of an emulsion crystal, assumed to be a sphere). As we shall show, this formula makes it possible to approach in a new way the quantitative treatment of the process of formation of a latent image when an ionizing particle passes through a crystal of the photographic emulsion. It is only necessary to bear in mind that Zhdanov' s formula, in the form in which it is written above, assumes that every crystal struck by the particle is developable. If, however, only parts of the crystals become developable, then the right-hand side of (1) must be supplemented by a factor P, characterizing the probability of development.

To determine P, let us assume that the passage of a particle through a crystal creates in it a sufficient number of conduction electrons for the subsequent formation of a development center only in the case when the path of the particle in the crystal exceeds some minimum length l, or, what is the same thing, passes within a sphere of diameter $\delta = \sqrt{d^2 - l^2}$, the tangent to which has length l within the crystal. Replacing the full sphere (diameter d) by an "effective" sphere (diameter δ) leads, in calculating ν, only to replacing $\pi d^2/4$ by $\pi\delta^2/4$, i.e.,

$$\nu = \frac{C_{\text{vol}}}{\pi d^3/6} \cdot \frac{\pi\delta^2}{4} = \frac{3C_{\text{vol}}}{2d}\left(\frac{\delta}{d}\right)^2, \tag{2}$$

whence

$$P = \left(\frac{\delta}{d}\right)^2 = 1 - \left(\frac{l}{d}\right)^2.$$

Recently K. S. Bogomolov et al. [2], proceeding from the idea that the path of a conduction electron is small compared with the dimensions of the crystal, showed experimentally that only the passage of a particle through a certain near-surface zone ("shell") of the crystal is effective; moreover, for any values of d, the thickness of the "shell" b is about $0.03\,\mu$ (from earlier data of other authors [3] it followed that b is substantially larger, namely $\sim 0.2\,\mu$). The minimum path length in the crystal l in this case is no longer a single-valued function of the distance δ from its center (Fig. 1). Therefore, instead of δ (see formula (2)), we now have δ_1 and δ_2—the diameters of two spheres, the tangents to which have length l within the "shell" of the crystal.

It can be shown that in this case

$$\nu = \frac{C_{\text{ob}}}{\pi d^3/6}\,\frac{\pi\delta_2^2 - \pi\delta_1^2}{4} = \frac{3C_{\text{ob}}}{2d}\,\frac{\delta_2^2 - \delta_1^2}{d^2}, \tag{3}$$

whence

$$P = \frac{\delta_2^2 - \delta_1^2}{d^2}.$$

In any case, formulas (2) or, respectively, (3), make it possible, on the basis of the values C_{ob} and d known for the given emulsion and the value ν determined experimentally, to find P, and then also the minimum path l that determines the photographically effective passage of the given particle through a crystal of the given emulsion.

Applying formula (2), we have

$$l = d\sqrt{1-P} = d\sqrt{1 - \frac{2\nu d}{3C_{\text{ob}}}}. \tag{4}$$

Applying formula (3), we find l from the solution of a system of three equations –formula (3) and two relations,

$$l = \sqrt{d^2 - \delta_2^2} \qquad \text{for } \delta > d - 2b;$$

$$l = \sqrt{d^2 - \delta_1^2} - \sqrt{(d-2b)^2 - \delta_1^2} \qquad \text{for } \delta \le d - 2b,$$

which are evident from Fig. 1, with respect to δ_1, δ_2, and l. For l one obtains a biquadratic equation

$$l^4 + \frac{8}{3}\left[\frac{\nu d^3}{8C_{\text{ob}}} - b(d-b)\right] l^2 - \frac{16}{3} b^2 (d-b)^2 = 0, \tag{5}$$

Fig. 1 diagram

Figure 1: Fig. 1 diagram

which has one real positive root. Note that formulas (4) and (5) do not lead to identical numerical values of l, and the differences increase as b/d decreases; however, for most nuclear emulsions, where $d \sim 0.2$–$0.3\,\mu$, the "shell" constitutes a large part of the crystal volume, and therefore the differences are small.

Fig. 1. $OE = d'/2$; $OF = d/2 - b$;
$AC = DE = l_i/2$; $OB = \delta_1/2$; $OA = \delta_2/2$

Knowing l, one can determine the minimum number n of conduction electrons necessary to impart developability to a crystal of the given emulsion. If the stopping power of AgHal is ~ 3000 ([4]), then the energy loss dE/dx is about 700 eV per $1\,\mu$ of path in AgHal for a particle with minimum ionizing ability. Since the excitation by a particle of one electron requires ~ 5.8 eV ([5]), the energy lost by the particle will lead to the liberation of $n = 700/5.8\,l$ conduction electrons in one crystal. For a particle with another value of dE/dx we have

$$n \cong 120 \frac{dE/dx}{(dE/dx)_{\min}} l.$$

As we have shown ([6]), the value of n corresponding to the threshold of developability is related to the number of sensitivity centers of the crystal N and to the minimum number of Ag atoms in the development center n_0 by the relation

$$n = N(n_0 - 1) + 1, \tag{7}$$

where n_0, and sometimes also N, can be determined independently. Then successive application of formulas (4) or (5), (6), and (7) to the analysis of tracks

particles with the limiting energy still recorded by the given emulsion makes it possible to determine the losses of conduction electrons, if substitution of the known N, n_0, and n into (7) leads to an inequality, and, if N is not known, to determine it.

The present note does not aim to give an exhaustive quantitative treatment of the formation of the latent image by ionizing particles. We shall therefore demonstrate only two examples of application of the proposed method to the analysis of particle tracks.

In one of our experiments two emulsions with different sensitivity to particles, obtained from one initial emulsion ($C_{\text{ob}} = 0.5$ and $d = 0.7\,\mu$) by varying the conditions of the second ripening, were exposed to electrons of medium energies from a C^{14} β-source and to relativistic electrons from cosmic radiation. For

Figure 2

Figure 2: Figure 2

both emulsions the values of N and n_0 were known; according to noninterchangeability data, n_0 at full development was 8 ± 1 for the more sensitive emulsion (hereafter denoted I) and 12 ± 1 for the less sensitive one (II), while according to electron-microscopic investigation N in both cases was 5, i.e., the sensitivity centers in the crystals of these emulsions differed in effectiveness (depth), and not in number. Tracks of relativistic electrons were found only in emulsion I, with $\nu = 0.3\,\mu^{-1}$; consequently emulsion II may be assigned $\nu \leq 0.15$–$0.18\,\mu^{-1}$ (below the discrimination threshold). Since for these emulsions $d \gg b$, formula (5) should be applied. The calculation gives, for emulsion I, $l = 0.3\,\mu$, $n = 36$, and for emulsion II $l > 0.38\,\mu$, $n > 46$. Substitution of n into formula (7) leads, for emulsion I, to an approximate equality, i.e., electron losses, if they exist, are very small, in good agreement with (7). For emulsion II, as expected, $n - 1 < N(n_0 - 1)$, which corresponds to nondevelopability.

Tracks of the entire C^{14} β-spectrum were found in both emulsions; for the initial sections of the tracks of the longest-range particles it was found that $\nu \simeq 0.6\,\mu^{-1}$ in emulsion I and $\nu \simeq 0.2\,\mu^{-1}$ in emulsion II. Taking $(dE/dx)_{E_{\max}C^{14}} = 1.7(dE/dx)_{\min}$, we obtain $l = 0.21\,\mu$ and $n = 43$ for emulsion I, and $l = 0.35\,\mu$ and $n = 71$ for emulsion II. Hence we obtain losses of conduction electrons of 20–25% for both emulsions, which is considerably larger than was found (7) for the finer-grained Ilford G-5 emulsion ($< 10\%$) at the same ionizing power.

One may think that these losses are connected not so much with recombination as with the formation of a deep latent image. Calculation by formula (4), in the present case little justified, leads to appreciably larger losses than indicated above, in complete contradiction with (7).

Fig. 2. a—π-mesons, b—β-particles

Interesting results are obtained by analysis, by the method described above, of data on track density in Ilford G-5 emulsion ($d = 0.3\,\mu$) for π-mesons with energies from 24 to 224 MeV ([8]) and β-particles with energies from 30 to 250 keV ([9]).

On the basis of formula (5), and not (4), and using data on dE/dx for particles of different energies ([4,10]), one can obtain the dependence of n on dE/dx, presented in Fig. 2. As can be seen, the minimum number of conduction electrons required for developability of a crystal increases with increasing ionizing power, i.e., a kind of decrease of the "quantum yield" is observed. Since for this emulsion the recombination losses of electrons at minimum ionizing power are negligibly small ([7]), and n_0, according to our data, is 7-8, then at

For $(dE/dx)_{\min}$, $N = \dfrac{n-1}{n_0 - 1}$ is easily found; it is equal to 4. Then, taking into account the data on recombination losses of electrons (7), one can also find N for other values of dE/dx, since n_0 remains unchanged; in the interval considered by us, N increases monotonically to 14-15. This means that, with an increase in the instantaneous concentration of conduction electrons in the crystal, the number of centers participating in the concentration of photolytic Ag increases at the expense of centers not intended for this role under optimum conditions. Such additional centers—for example, deep centers, or centers requiring, for transformation into development centers, a larger number of Ag atoms than the principal ones—compete with the principal centers and thereby reduce, along with the ever-increasing recombination, the efficiency of utilization of conduction electrons. A calculation of n and N, carried out in the same way by formula (4), gives qualitatively quite analogous results; the somewhat higher values of n and N obtained in this case are possibly due to the influence of processes not only in the "track," but also throughout the entire volume of the crystal. Then the difference between the values of n and N calculated from (4) and from (5) could serve to estimate the losses associated with the formation of the deep latent image.

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Note: Figure translations are in progress. See original paper for figures.