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# Response of photosensitive silver halide micro-crystals to multiple-charged particles

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**Abstract.** Temperature dependence of sensitivity of silver halide micro-crystals is theoretically examined for a wide range of momenta and charges of ionising particles. Our earlier results on the ionisation theory have now been extended for the interaction of multiple-charged particles with AgBr emulsion grains.

**Keywords.** Photosensitivity; silver halide-micro-crystals; multiple-charged particles.

## 1. Introduction

The sensitivity of photosensitive materials as well as the mechanism of latent image formation are not only influenced by the structure and composition of the silver halide grains but also by the momentum, charge of the ionising particle and the temperature of the photographic emulsion during exposure.

It has been reported that the latent image formed by exposing a photographic emulsion at liquid nitrogen temperature develops much more slowly than at room temperature (James *et al* 1961; James 1962; James and Veneslow 1965). At low temperatures some of the unique features of latent image formation cause the image centres to grow to a size which can be considered as the threshold of development. However, at room temperatures these centres continue to grow. Barkas (1963) has shown that the formation and behaviour of a photographic latent image at low temperature is related to the ionic conduction of the AgBr crystal and therefore a latent image cannot be formed until the temperature is raised. On the other hand, at high temperatures thermal agitation tends to destroy the image. According to Barkas, the maximum sensitivity may be around 0°C. Experiments at the Lawrence Radiation Laboratory with K-5 emulsions have shown a maximum of near constant sensitivity in the range $-20°\mathrm{C}$ to $+20°\mathrm{C}$. The sensitivity of a G-5 emulsion also drops at both high and low temperatures. A qualitative explanation of the experimentally observed facts has been attempted (Singh and Sharma 1976; James *et al* 1961; James and Vaneslow 1965; James 1962; Barkas 1963).

In the present study, we have proposed a theoretical model for understanding the response of photosensitive silver bromide material when exposed to particles of various momentum and charge at different temperatures using kinetic considerations.

## 2. Theoretical

Due to the passage of a charged particle the absorption of energy at a point within the silver halide grain generates an electron in the conduction band and a positive hole in the valence band. Electron-hole pairs are thus formed. The liberated electron-hole pairs exist in some initial states from which recombination is possible at recombination centres (Singh and Sharma 1976). Besides, the electrons migrate through the crystal lattice until they are trapped. The electrons can also be neutralised by interstitial silver ions to form atoms of silver usually on the surface of the grain. Thus, the number of electrons decreases with time as a result of the recombination of electrons with holes and the combination of electrons with interstitial $Ag^+$ ions. The total number of electrons effective ($\bar{n}$) in forming silver atoms after an infinite time is given by

$$\bar{n} = n_0 \exp(-\alpha\tau_n \bar{n}), \tag{1}$$

where $\alpha$ is recombination constant and $\tau_n$ is the time of neutralization. In G-5 emulsion, the maximum number of electrons is $n_0=46{\cdot}86\ (dE/dR)$, where $dE/dR$ is expressed in keV/$\mu$m.

The relationship between the rate of energy loss ($dE/dR$), charge ($Z$) and velocity ($\beta$) of the particle traversing the most sensitive G-5 emulsion (Fowler and Perkins 1951) is given as

$$dE/dR = 0{\cdot}587\, Z^2\, \beta^{-1{\cdot}46}. \tag{2}$$

The effective number of electrons ($\bar{n}$) for multiple charged particles can be calculated using (1) and (2). The magnitude of $\alpha$ and $\tau_n$ are expressed as (Singh and Sharma 1976)

$$\alpha = 3{\cdot}88\times 10^{19}\, \sigma_t\, (T/300)^{1/2}\ (\mathrm{sec}^{-1}),$$

where $\sigma_t$ is capture cross-section of the traps ($\approx 10^{-16}$ cm$^2$) and

$$\tau_n = \frac{1{\cdot}4\times 10^{-15}\, T \exp\left(-\ 3{\cdot}88 - \dfrac{0{\cdot}15\ \mathrm{eV}}{kT}\right)}{\sqrt{2}\ [\exp(-\ 0{\cdot}32\ \mathrm{eV}/kT) + \exp(-\ 0{\cdot}92\ \mathrm{eV}/2kT)]},$$

where $k$ is the Boltzmann's constant and $T$ is the absolute temperature.

The process by which a grain develops is strictly related to the specific ionisation of the charged particle and the intrinsic characteristics of the AgBr grains. Calculation of the grain density involves a parameter called 'probability of development of a grain.' If $g_0$ is the number of grains per unit length in the undeveloped emulsion and $\pi$, the probability that a grain will be sensitised and developed, then the number of developed grains per unit length is $\pi g_0$ and is known as primary ionisation ($g_p$) given by (Singh and Sharma 1975)

$$g_p = \{1 - 2\lambda_0^{-2}\, [1 - \exp(-\ \lambda_0) - \lambda_0 \exp(-\ \lambda_0)]\}\, g_0, \tag{3}$$

where $\lambda_0 = 19{\cdot}6\times10^{-2}\, dE/dR \exp(-a\, \tau_n\, \bar{n})$.

$dE/dR$ is the specific energy loss of the ionising charged particle. For unprocessed G-5 emulsion, $g_0=275/100\ \mu$m. The variation of $\bar{n}$ and $g_p$ as functions of $dE/dR$ is shown in figure 1.

Apart from the primary ionisation, which is directly affected by the charged particle, a few other secondary grains are also developed due to the outgoing δ-rays. Hence the total grain density is given by (Singh and Sharma 1975, 1976; Nicoletta *et al* 1967).

$$g = g_p + 0{\cdot}125\, g_s, \tag{4}$$

where $g_s$ is the secondary grain density.

Thus our experimental value ($g$=19·64 grains per 100 $\mu$m) gives a $g_p$ value of 17·2 grains per 100 $\mu$m. For a primary grain density at minimum ionisation, the corresponding value of $dE/dR$ from figure 1 is 0·5 keV/$\mu$m at 300°K. This is a reasonable value of energy loss associated with the production of an observable grain density around 20 grains per 100 $\mu$m.

## 3. Results and discussion

Figure 2 shows the plots of theoretical values of $\bar{n}$ computed from (1) for various values of $dE/dR$ for a temperature range 233-350°K. It is seen that most of the curves show an increase up to room temperature, while beyond this region a saturation is observed. These curves do not quantitatively explain the fall at high temperatures, as stated by Barkas for G-5 emulsion experiments.

The results given in figure 2 show the variation of $g_p$ with temperature for different values of $dE/dR$. Ignoring the variation of $g_p$ at lower temperatures, it is our conclusion that the curves with specific ionisation >2 or 3 keV/$\mu$m are linear upto a

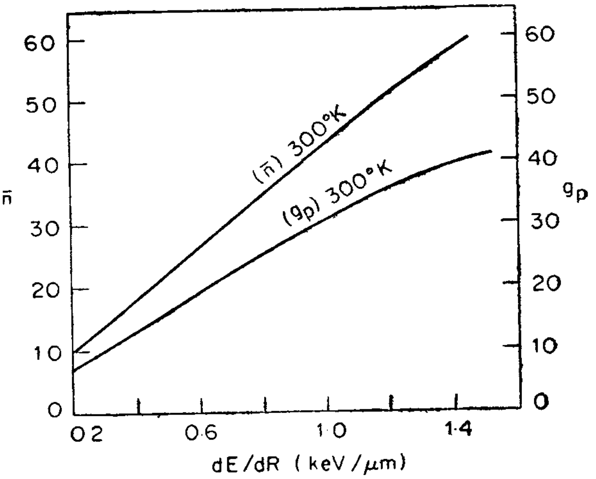

**Figure 1.** Variation of $\bar{n}$ (or $g_p$) with $dE/dR$ at room temperature.

temperature ~ 300°K, while beyond this region a saturation is observed. The curve for $dE/dR \sim 1$ keV/$\mu$m represents the grain density of near minimum ionising particle tracks which remain almost independent of temperature over a wide range.

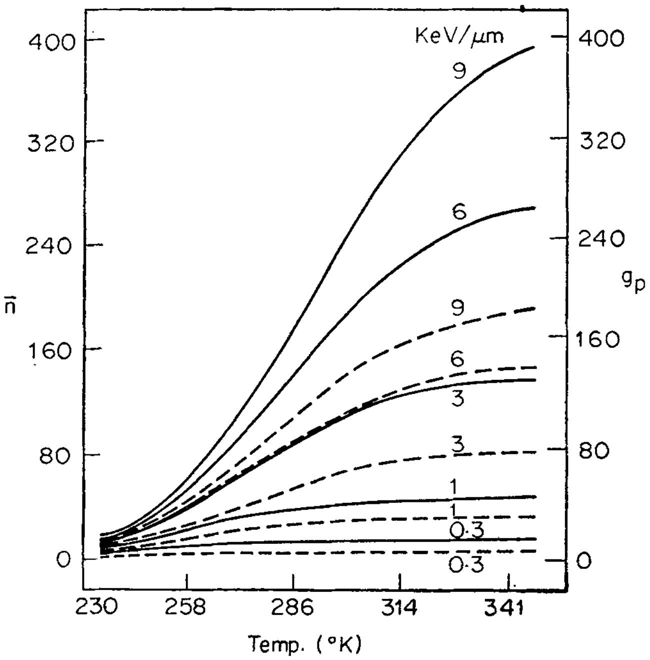

**Figure 2.** Variation of number of electrons and primary ionisation with temperature in G-5 emulsions for various values of $dE/dR$.

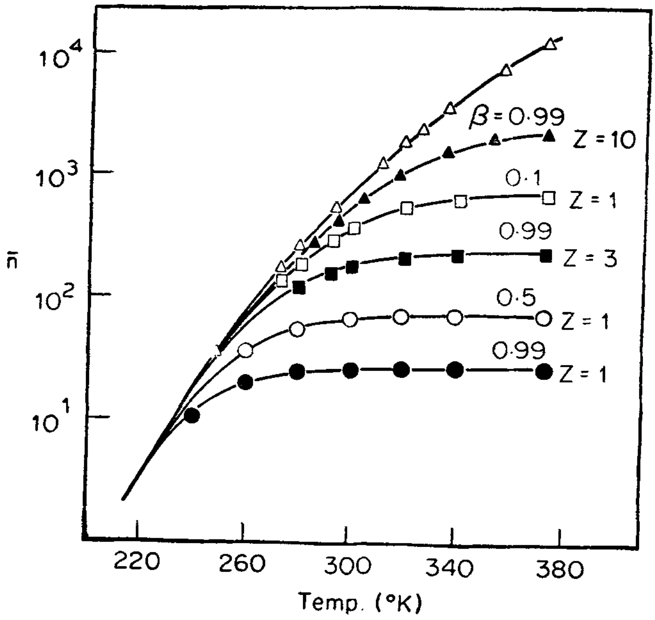

**Figure 3.** Variation of $\bar{n}$ with temperature (Z) for different values of $Z$ and $\beta$.

The experimental results of Dyer and Heckman (1967) for such emulsions also indicate temperature independence of sensitivity in the temperature range 253°K to 323°K.

The variation of $\bar{n}$ with $T$ for different values of $Z$ and of the particle in the temperature range 220-373°K is shown in figure 3. The curves indicate that $\bar{n}$ reaches a constant value at a very low $\beta$ and remains almost oonstant for all further values of $Z$. Moreover, these values are independent of charge and secondary ionisation. Though the value has been taken as low as $10^{-5}$, when a very heavy ionisation is created, the results indicate that $\bar{n}$ remains constant. However, there does not seem to be any necessity for considering a $\beta$ value less than $10^{-3}$. The number of effective electrons for various values of $\beta$ at higher temperatures becomes significant. The minimum grain sensitivity for particles of $Z=1$( i.e. hydrogen nucleus), $\beta=0{\cdot}99$ for the saturation region (beyond 270°K), corresponds to nearly 27 effective electrons. The sensitivity becomes nearly thrice the minimum sensitivity for particles of $Z=1$ and $\beta=0{\cdot}5$. When $Z=1$ and $\beta=0{\cdot}1$, the value is nearly 25 times the minimum value. Similar variations are observed for particles of higher charges and similar velocity ranges. Figure 3 also indicates that at very low temperatures (below 220° irrespective of any momentum and charge of the particle) $\bar{n}$ will always be less than 1 which means that no latent image formation may take place at such a low temperature.

Figures 4 and 5 represent the variation of $\bar{n}$ with various values of $\beta$ and $Z$ of the particle traversing the emulsion if exposed to 240°, 293° and 340°K temperatures. The variation at a low temperature (240°K) indicates that for slowly moving particle with $\beta=0{\cdot}1$, the values of $\bar{n}$ are independent of $Z$ while there is a small variation for a relativistic particle with $\beta=0{\cdot}99$. But beyond $Z=10$ (neon nucleus) it becomes independent of $Z$. As the temperature is raised to room temperature, $\bar{n}$ values are

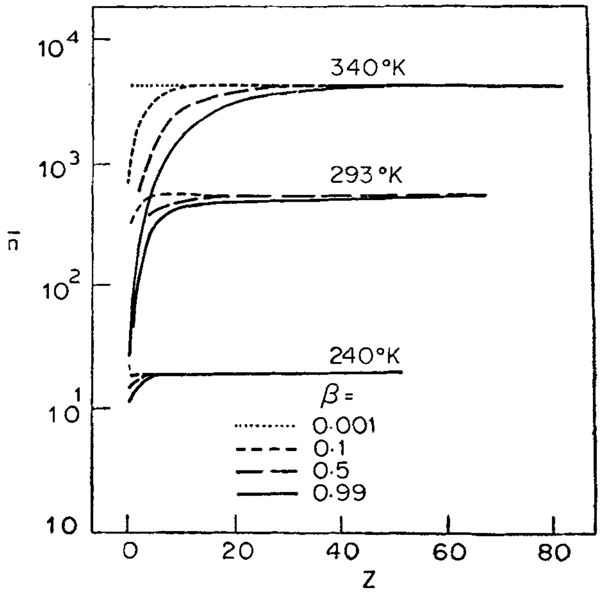

**Figure 4.** Variation of $\bar{n}$ with charge ($Z$) for different values of $\beta$ at three selected temperatures.

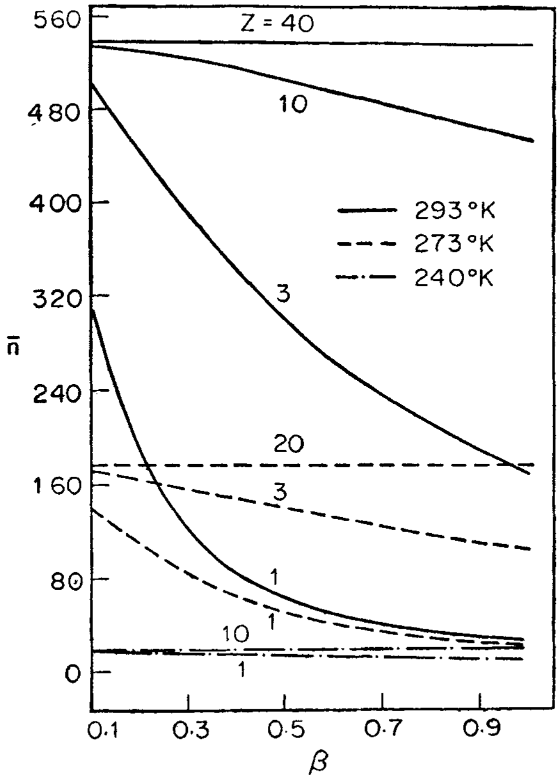

**Figure 5.** Variation of $\bar{n}$ with $\beta$ for different values of $Z$ at three selected temperatures.

almost independent of $Z$ beyond $Z$=60. When the temperature is raised to 340°K, the curves are similar to those at room temperature and becomes independent of $Z$ and $\beta$ beyond $Z$=80.

It is hoped that our results have brought forth the utility of photographic emulsions at different temperatures of exposure. The limited grain sensitivity at low temperatures and the increasing values at moderate and high temperatures predicted on the basis of the present model appears to give convincing support to the process of latent image formation, recombination and trapping.

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