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# ANALYSIS OF A BREAKUP USING MEAN TRACK WIDTH AND BLOB MEASUREMENTS*

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The consistency of the mean track width theory and the linear grain density theory of Katz and Kobetich[1]) is confirmed through the analysis of a breakup event composed of a primary and three visible fragments.

## 1. Introduction

A simple, flat break-up event occurs at a depth of 116 μm below the surface of a 400 μm Ilford G.5 emulsion pellicle exposed at balloon altitude over Fort Churchill. The observed event consists of 2 grainy fragments, a heavy fragment, and a heavy primary (fig. 1). All fragments end in the emulsion stack.

Blob density measurements were made of the two grainy fragments, and mean track-width measurements were made of the heavy fragment and the heavy primary. The number of blobs per unit length was measured using a Leitz Orthoplan microscope equipped with a Leitz Plano 100 × oil immersion lens and a tilting-rotating stage. The range was measured from the midpoint of the blob count interval. Using the same apparatus, mean track-width measurements were made by photographing the track (3000 ×) in 50 μm segments, tracing the profile of the track core manually, and measuring the area within a segment profile with a planimeter.

Recent analyses of the response of nuclear emulsion to charged particles[1,2]) are based on the assumption that the probability $P$ for rendering an emulsion grain developable depends on the average dose $\bar{E}$ experienced by a grain, according to the relation

$$P = 1 - e^{-E/E_0}, \tag{1}$$

where $E_0$ is the dose at which 63% of the grains are developed. To describe the track of a charged particle, one first calculates the dose $\bar{E}(t)$, deposited by secondary electrons (δ-rays) ejected by the passing ion, in a grain whose center is $t$ distant from the ion's path. By means of eq. (1), this is converted to the spatial distribution of developed grains, from which one can calculate theoretical values of measurable track properties, such as the blackness profile, the track width, the linear grain or blob density. These properties then depend on $E_0$, the number of undeveloped grains per unit volume, the

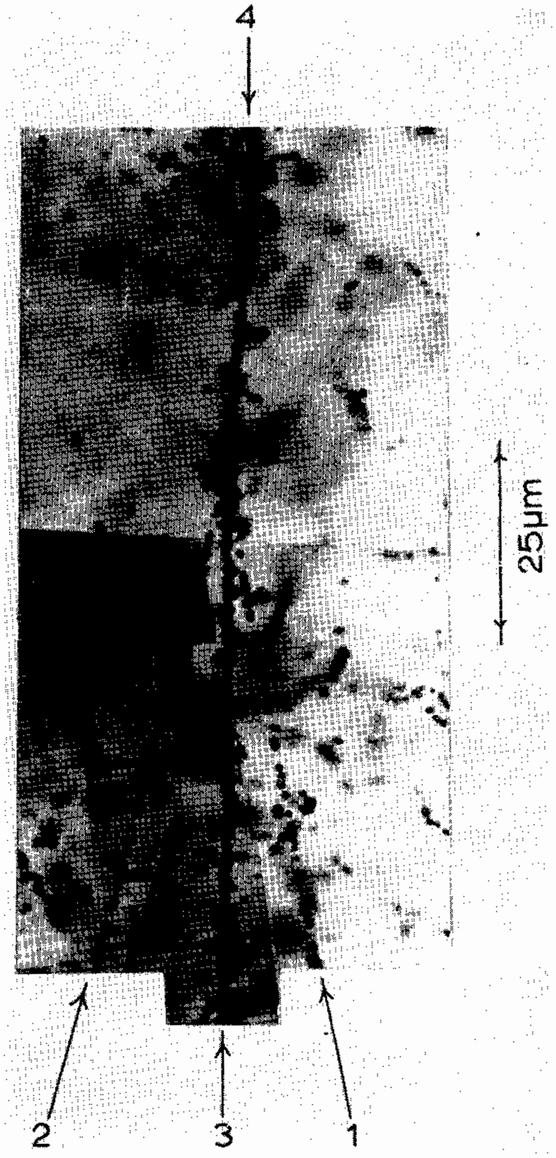

Fig. 1. Montage of the breakup event with two grainy fragments (1,2) identified as protons, a heavy fragment (3) identified as carbon, and a heavy primary (4) identified as $^{16}$O. Details are given in table 1.

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size of an undeveloped grain, and the size of a developed grain, which depend on the emulsion and its processing.

The decision as to where the edge of a track lies, or what constitutes a blob depends somewhat on the observer. Within the framework of the theory we say that an observer makes a choice of $P$ which he identifies as the location of a track edge, which amounts to choosing a value of $\bar{E}$ to identify with the track edge. The relation of track width to the theory is a fairly simple one. The measured width as a function of range is compared to calculated profiles of $\bar{E}$ as a function of range for different $z$[1]). To relate blob density vs range measurements to the theory requires a somewhat longer route. The blob density $B(\beta)$ at a portion of a gapped track where the ion velocity is $\beta c$ is related to the linear density of developed grains $g$ through the statistically based expression

$$B(\beta) = g\,\mathrm{e}^{-g\alpha} \tag{2}$$

given by Barkas[3]) in terms of the parameter $\alpha$, which is the sum of the mean diameter of a developed grain and the minimum gap-length detectable by an observer and found from maximum values of blob-density measurements. In the present work the values of $\alpha = 0.80\ \mu\text{m}$ and $= 0.85\ \mu\text{m}$ were found by two observers.

It has been shown by Katz and Kobetich[1]) that an emulsion grain through which an ion of charge $ze$ passes at speed $\beta c$ experiences a mean dose of

$$\bar{E} = \varepsilon z^2/\beta^2 \tag{3}$$

in which $\varepsilon$ depends on the size of the grain, and has the value 605 erg/cm$^3$ in G.5 emulsion. Thus if $g_0$ is the saturation grain density along a track (= 5000 grains/ /mm in G.5 emulsion), the theory of particle tracks asserts that the grain count along a gapped track is given by

$$g/g_0 = 1 - \mathrm{e}^{-(\varepsilon z^2/\beta^2 E_0)}. \tag{4}$$

The combination of eq. (4) and eq. (2) makes it possible to find the blob count as a function of $z$, $\beta$, and $E_0$. For direct comparison with experiment we convert this relation numerically to one in which the blob count is expressed as a function of $z$, range, and $E_0$ through use of the tables of Barkas and Berger[4]).

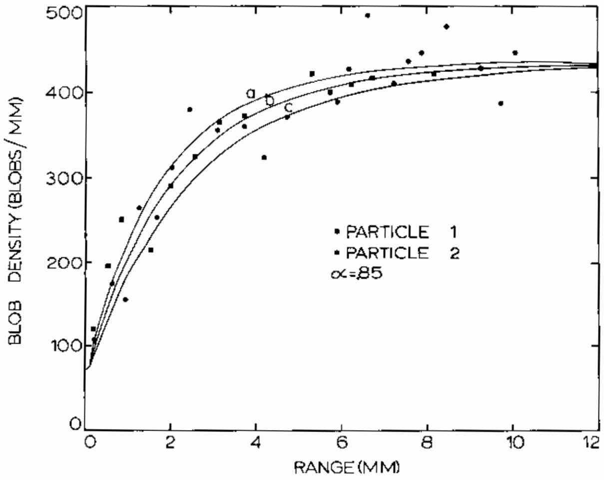

Fig. 2. Blob density vs range for the two grainy fragments. The theoretical curves are calculated for protons with assignment $E_0 = 22\,000$(a), $20\,000$(b), and $18\,000$(c) erg/cm$^3$. The observer parameter assignment is $\alpha = 0.85\ \mu$m.

## 2. Analysis of a breakup

Since the breakup is simple, it is taken to arise from a grazing or Coulombic collision, so that the momentum transferred to the emulsion nucleus is small. All fragments are taken to come from the primary ion and to have about the same velocity as the primary ion at breakup.

The emulsion response parameter $E_0$ is nearly uniform for all points in the center of the emulsion, but less uniform near the edges and surfaces. Blob density measurements made of the two grainy fragments which go through several pellicles were taken in the center portion of each pellicle, or were checked for consistency with data taken in the center portion, as were the mean track width measurements of the heavy primary, which goes through several pellicles. The breakup event itself and the heavy fragment are in the center portion of one pellicle.

Visual inspection of the two grainy fragments

TABLE 1

| Track number | amu | Atomic number | Residual range ($\mu$m) | $\beta = v/c$ at breakup | Direction cosines at breakup |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 7 500 | 0.30 | (0.98, 0.20 −0.02)[a] |
| 2 | 1 | 1 | 10 400 | 0.32 | (0.98, −0.18, −0.12) |
| 3 | 12 | 6 | 3 400 | 0.32 | (0.99, 0.04, 0.08) |
| | 13 | | | 0.32 | |
| | 14[b] | | | 0.31 | |
| 4 | 16 | 8 | (2 500)[c] | 0.32 | (1.0, 0.0, 0.0) |

[a] The $x, y$ coordinates are in the plane of fig. 1, with the $x$ axis being in the direction of the primary ion.

[b] Alternate possible assignments of the mass and speed of the carbon fragment.

[c] The residual range of the heavy primary is computed from the mass, charge, and assigned velocity at breakup.

suggests that they are protons. Comparison of blob density data for these particles indicates that they have the same mass and charge. When the blob data are compared to that calculated for protons, the particles are definitely identified as protons. The best fit of the blob density theory to blob measurements for these protons gives $E_0 = 20\,000 \pm 2\,000$ erg/cm$^3$ (fig. 2).

The mean track width theory, with $E_0 = 20\,000$ erg//cm$^3$, identifies the heavy fragment and the heavy primary as carbon and oxygen, respectively. The "track edge" is associated with a dose of 7 200 erg/cm$^3$, a value consistent with past work and implying that the observer chose to locate the track edge where $P = 0.3$.

Thus the break-up event is taken to consist of an incident $^{16}$O nucleus fragmenting into 2 protons, from 0 to 2 neutrons (to conserve mass), and a carbon nucleus of mass 12, 13, or 14, since no beta particle is observed and neither range nor width measurements admit better mass resolution.

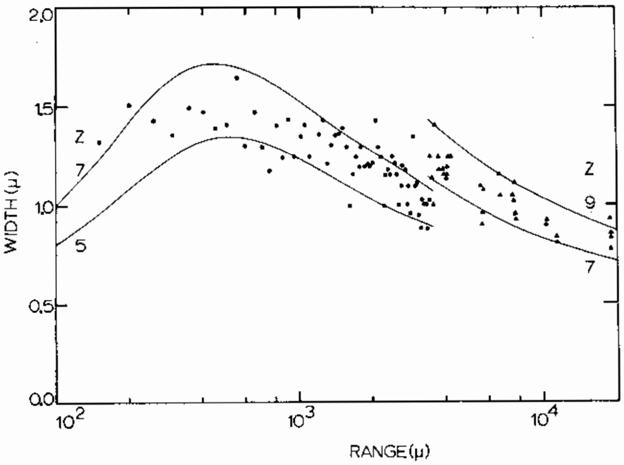

Fig. 3. Mean track width vs range for the incident ion and heavy fragment. The theoretical curves of indicated atomic number are calculated from the assignment $E_0 = 20\,000$ erg/cm$^3$. The total track length in emulsion of the primary is 4.2 cm beyond the breakup, but only the 1.6 cm nearest the breakup is used for width measurements, because the remaining 2.6 cm is gapped (too much for track width measurement but not enough for usable blob counts) in a manner qualitatively consistent with its identification as $^{16}$O and with the assigned emulsion parameters.

Momentum and range analyses confirm these conclusions (table 1). By taking neutrons to have the same velocity as the incident ion, a momentum analysis suggests that 6–8% of the total momentum is carried away by the target nucleus. Since a target proton given 6–8% of the incident momentum would leave an observable track, the target nucleus must be more massive. Other emulsion nuclei might acquire from 0.2% (Ag) to 2% (C) of the total energy.

## 3. Discussion

Earlier investigations of the response of nuclear emulsion to charged particles[1,2]) have examined separately either grain count, track width, particle track blackness, or the blackness of emulsion exposed to beams of monoenergetic electrons. In each case it has been possible to fit the observed data with a single model (1-or-more hit to dose) by assigning reasonable values of the parameters. The present break-up event affords the best possibility of testing the model of track width and blob density in emulsion at constant $E_0$. The theory of track formation is tested with positively identified charged particles of energy presently beyond the reach of accelerators, in the grain-count regime as well as in the track-width regime. The analysis is consistent with the track model, based on the assumption that the energy deposited by secondary electrons is responsible for track structure. There seems to be no compelling need to imagine that there are special processes taking place in a "track core" which are distinct from those taking place along a track edge.

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