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Formation of Particle Tracks

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Abstract

The formation of particle tracks, and such phenomena as the detection of charged particles and the damage produced by charged particles, are intimately related to the spatial distribution of ionization energy deposited by δ-rays. Changes in the spectrum of δ-rays with the velocity of the primary particle imply that linear measures of the interaction of the primary particle with the medium, such as specific energy loss, or primary ionization, are unsatisfactory measures of effects produced in the medium, for they contain no knowledge of the spatial deposition of the lost energy.

1. Introduction

Damage produced in condensed matter by γ-rays and energetic charged particles arises from similar causes. In both cases most of the damage arises from the interaction of secondary electrons with the medium. The principal difference between γ-irradiation and charged particle irradiation lies in the spatial distribution of secondary electrons. For γ-irradiation, the secondary electrons are widely distributed throughout the medium; while for proton and heavy ion bombardment, the secondary electrons are clustered around the ion's path, and deposit their energy nearly inversely with the square of the distance from the path, to distances up to the range of the most energetic δ-ray. The energy deposition gives rise to bond rupture, and to spatial and molecular rearrangement. The resulting chemical and physical alterations of the medium are detected in a variety of ways, sensitive to different aspects of the phenomenon. The creation of internal stress causes lattice alterations, detected by the electron microscope. Molecular rearrangements, such as the creation of free radicals, alter the etchability, and the absorption of electromagnetic radiation. The creation and migration of excitons sensitizes the photographic grain. Aside from obvious geometric differences, the response of detectors to heavy particles and to γ-rays must be intimately related. In small subvolumes near the ion's path, we assume that the response of the medium is as if the subvolume were part of a larger system irradiated with γ-rays to the same energy deposition dosage. We further assume that within the subvolume the energy deposition is random. Thus the response of the medium to irradiation can be expected to resemble the cumulative Poisson distribution, rather like a photographic sensitivity curve.

Several detection systems have been analyzed on this basis. A one-or-more hit response describes the behavior of nuclear emulsions to charged particles, yielding grain counts up to minimum ionization, blackness, and track width. It describes the response of molecules of biological significance to heavy ions. It describes the response of scintillation counters to heavy ions. In the limit of many-hits, the cumulative Poisson distribution approaches a step function, implying a threshold response, appropriate to the hypothesis that many damaging events must be produced in large molecules to alter their chemical reactivity substantially, as in the formation of etchable tracks in dielectrics.

In conductors, the concept of a localized bond loses its meaning. The coupling between electrons and the lattice is weak, so that the energy acquired by secondary electrons is much degraded before it interacts with the lattice, and appears as lattice excitation (heat) rather than lattice disruption. Metals are undamaged at very large γ-ray doses. With increase in electrical resistivity, the coupling between electrons and the lattice increases. A broad threshold for track formation appears at about 100 ohm-cm, consistent with this view.

2. Spatial Distribution of Ionization Energy

To find the spatial distribution of ionization energy we must resort to calculation. We need a δ-ray distribution formula, doubly differential in energy and an-

gle, and electron energy dissipation data, valid down to electron energies of about 10 eV. Since this information is not available, we must make use of whatever information is available, extrapolating from observation where necessary, checking the extrapolations interactively with the phenomenon under investigation.

In all cases, the δ-ray distribution formula, differential in energy, calculated for free electrons is used. For electrons in a medium, it is assumed that the energy which would be given to a free electron is the energy transferred to the bound electron, and is equal to the sum of the binding energy and the kinetic energy acquired by the bound electron.

When interest centers on effects close to the ion's path, say within 1,000 Å, all δ-rays are taken to be normally ejected, for most of the energy deposited is associated with δ-rays of low energy which are ejected in grazing collisions. This is the case for the bombardment of biological molecules, for scintillation counters, and for the formation of etchable tracks in dielectrics.

Where the events of interest are microns distant from the ion's path the angular distribution is adjusted to give best agreement with experimental observation. Thus for track formation in emulsion distributions of the form $5\cos^4\theta$, and in most recent work the classical distribution for the collision of two free particles, have been used.

In all work up to the present time, the direct excitations of the medium produced by the passing ion have been neglected. The validity of this neglect may be due to the fact that the response of a medium is saturable, and that the energy deposition from δ-rays alone may be sufficient to saturate the detector response at distances to which the excitation energy may migrate.

Electron energy dissipation data has been systematized in a computer algorithm, which yields calculations of the energy dissipation in good agreement with

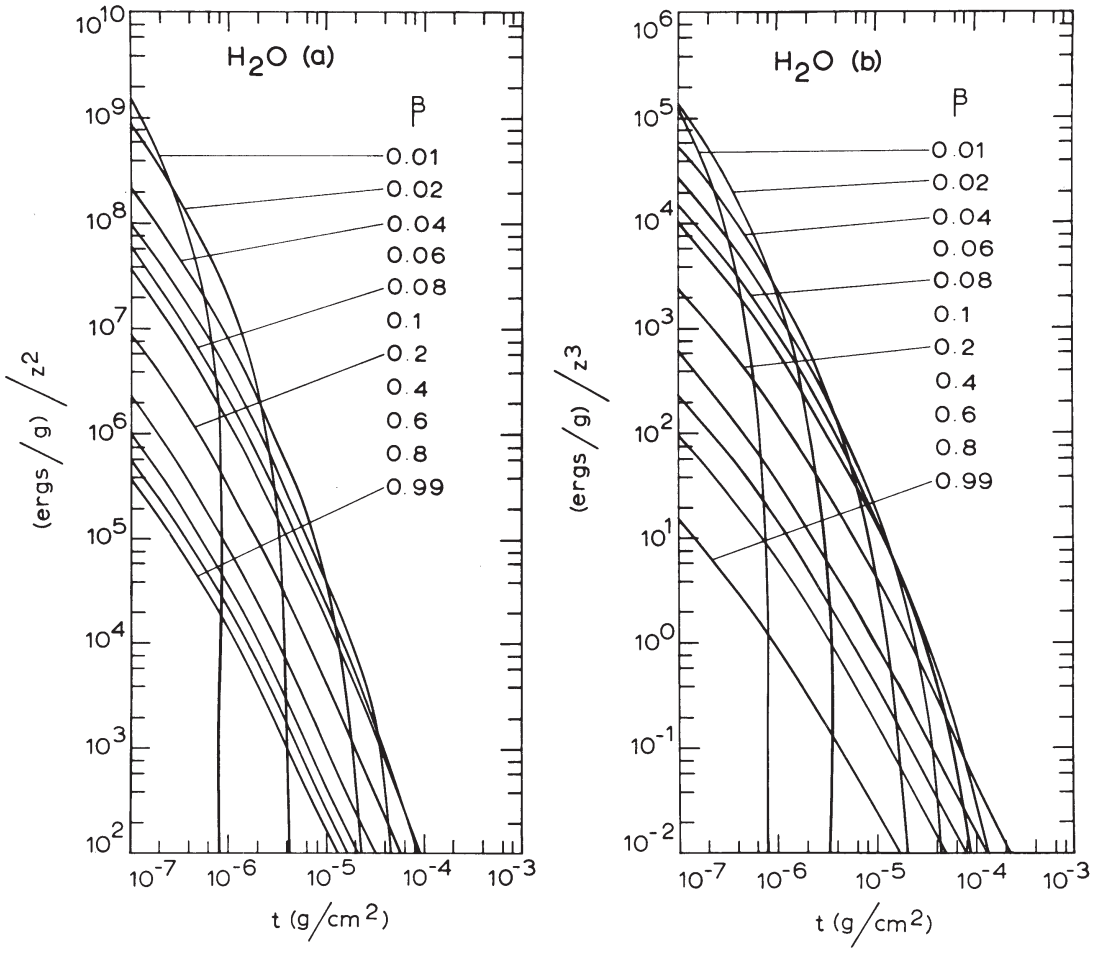

Figure 1. Spatial distribution of ionization energy, $E(t)/z^2$, in water as a function of the distance t from the ion's path, calculated from the δ-ray distribution formula, and the assumption of normal ejection. Applicable to organic materials, where interest centers relatively close to the ion's path.[4] To find the energy deposition at distance t the contribution from (a) must be added to that from (b).

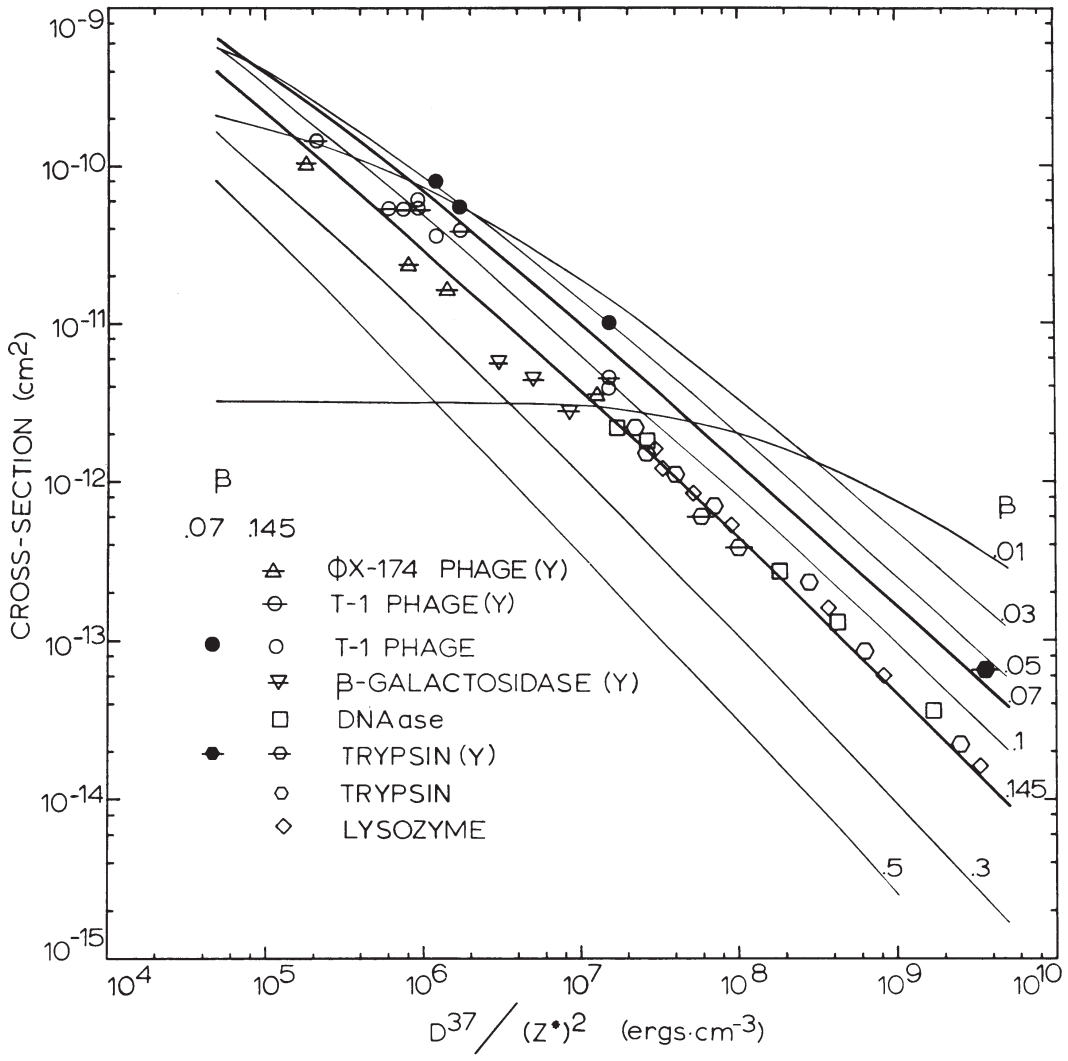

Figure 2. Cross section for the inactivation of dry enzymes and viruses, in relation to the critical dose ($E_0 = D^{37}$) divided by the square of the effective charge of the bombarding ion. Plotted points crossed with a horizontal bar were obtained at the Yale HILAC (Y), while other points were obtained at the Berkeley HILAC. Lines arise from the theory.[2]

experiment, down to the lowest energies with which energy dissipation observations have been made, about 1 keV. The algorithm is used to extrapolate to lower energies.

At the present time it appears that the basic construction of the model is sound, though details in the calculation of the spatial distribution of ionization energy need reinforcement. That reinforcement may come from interactive application of the model to study of radiation detection and damage phenomena.

Results

To calculate the response of a detector to charged ***P*** particles, we must find the spatial deposition of ionization energy $E(t)$ as a function of t, the distance from the ion's path. Next, we must average the deposited energy over the volume of the sensitive cell, nominally taken to be a sphere of appropriate radius a_0, to find $\bar{E}(t)$, important where interest is centered on events within 2 a_0 of the ion's path, and this region is not saturated. At larger distances, the average and point distributions of energy dosage are sufficiently close to each other that the difference may be neglected, as in the "point-target approximation."

In those circumstances where the 1-hit model is appropriate, the probability P that an event of interest will take place is given by the expression

$$P = 1 - \exp(-\bar{E}(t)/E_0), \qquad (3.1)$$

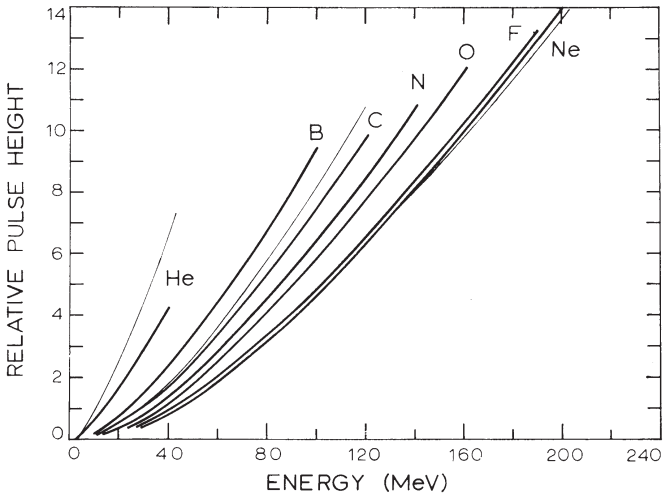

Figure 3. Experimental values of relative pulse height in NaI(T1) from a spectrum of incident ions plotted against ion energy as light lines, while normalized theoretical results are plotted as heavy lines. In some cases the light lines are obscured by the heavy lines. (Katz and Kobetich, 1968-2).

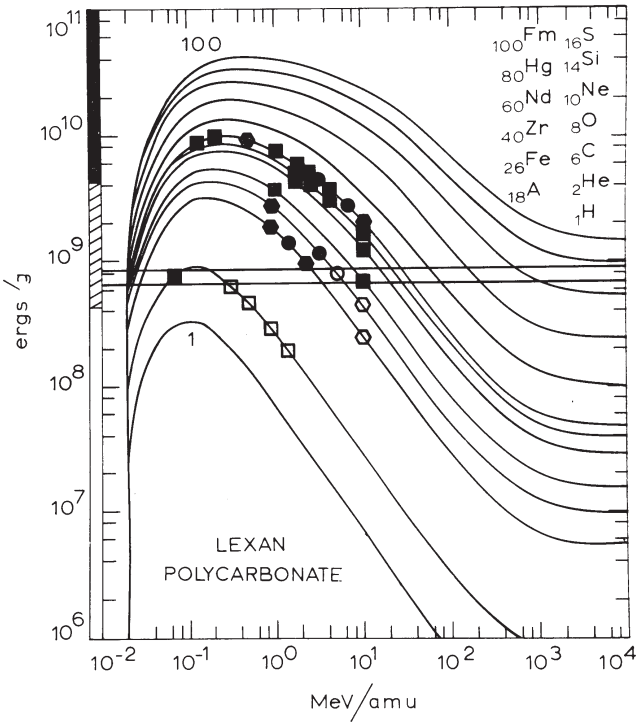

Figure 4. Dosage of ionization energy in Lexan polycarbonate at 2×10^{-7} g/cm^2 (17 Å) from the ion's path for a spectrum of ions and ion energies. Superimposed experimental points are solid if etchable tracks are formed, and are hollow if not.[5]

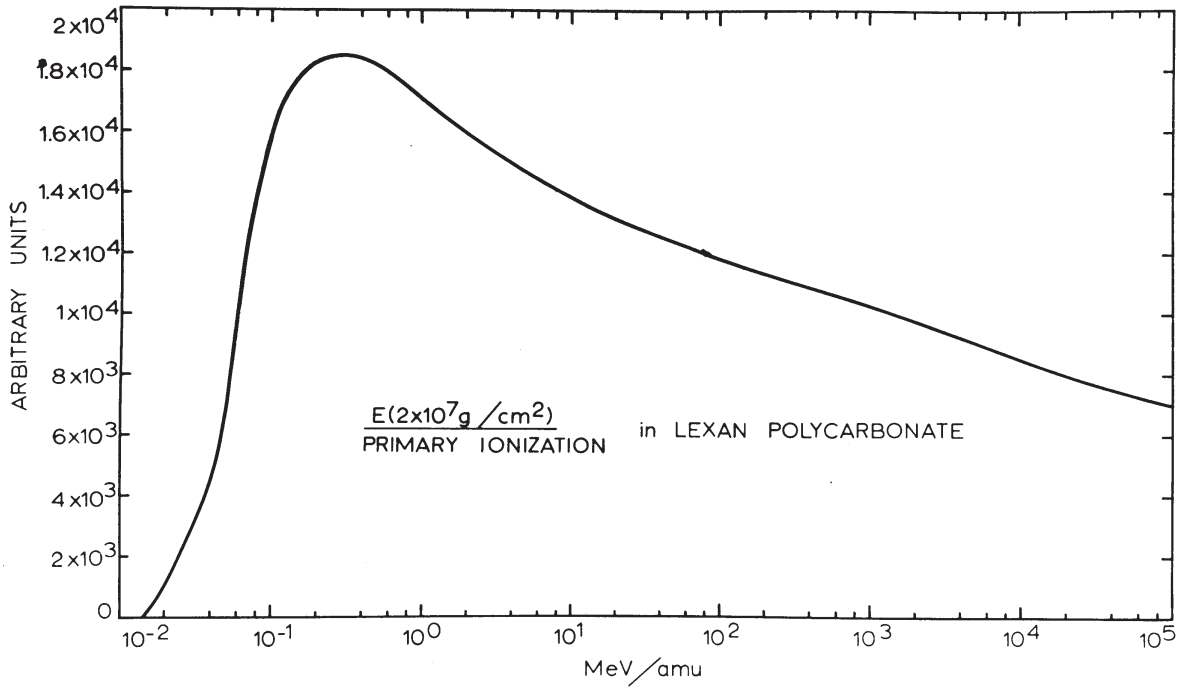

Figure 5. The ratio of two criteria for track formation in dielectrics: energy deposition at × 10^{-7} g/cm^2 [5] / total primary ionization(s) in Lexan polycarbonate. If these criteria are calibrated by bombardment with machine accelerated ions at 1-10 MeV/amu, the changing ratio of the two criteria implies that the energy deposition criterion will yield a higher identification for relativistic ion tracks than will the primary ionization criterion.

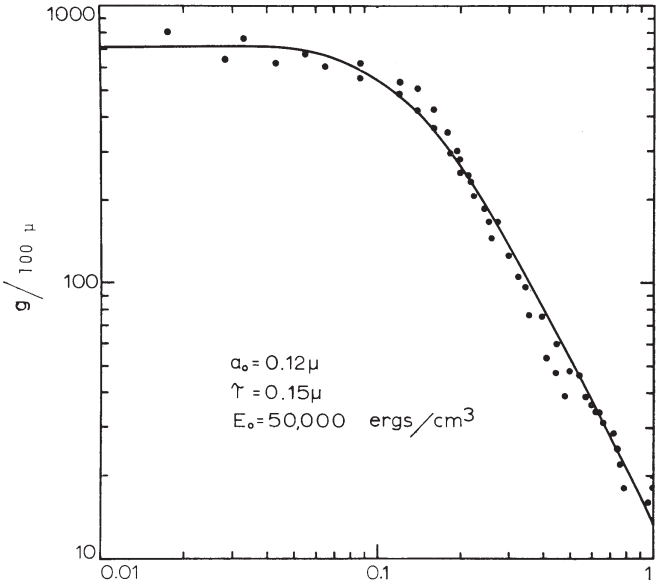

Figure 6. Grain count in K-5 emulsion for singly charged particles [9] as a function of β, plotted as points, while theoretical calculations are plotted as a line.[6]

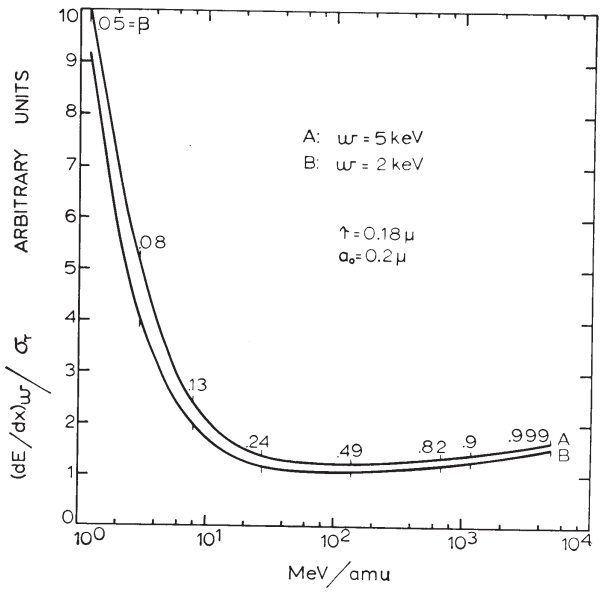

Figure 7. The ratio of two criteria for grain counts: $(dE/dx)_{\text{restricted}}$ (in AgBr)[1]/$\sigma\tau$[6]

where E_0 is the characteristic dose for $P = 0.63$, and cross-section σ for the interaction of the incident particle with the medium is the integrated probability, over all distances from the ion's path, as in the expression

$$\sigma = \int_0^\infty 2\pi\, t\,dt\{1 - \exp(-E(t)/E_0)) \qquad (3.2)$$

If, as in grain counting, the observer limits those events he counts as within a distance τ of the particle's path, then a partial cross-section is appropriate to the observation, labeled σ_τ, obtained by reducing the upper limit of the integral of Equation (3.2) from ∞ to τ.

Where interest lies in the spatial distribution of events rather than in the total interaction, as in observations of variations of photographic blackness with distance from the ion's path, or in the width of particle tracks in emulsion, Equation (3.1) must be used in conjunction with the calculated function $\bar{E}(t)$, to find $P(t)$, the spatial distribution of the probability for an event of interest to occur.

In the event that the process of interest is better described as a many-hit process than as a 1-hit process, an additional criterion must be applied to the system to relate the calculation of $E(t)$ to the observed phenomenon. For the formation of etchable tracks in dielectrics, it has been assumed that the damage must take place out to some characteristic radius, determined by the size of the solvent complex, so that the solvent can pass freely down the damaged channel. Again the magnitude of the damage is related to the deposited dose of ionization energy. At the critical radius, the dose must be sufficiently large to produce observable damage to the bulk material, when irradiated with γ-rays. When calculations of the dose at about 20 Å are plotted as a function of ion energy, and the formation or non-formation of tracks is superimposed on these plots, consistent results are obtained; that is, there is a critical dosage which separates formation from non-formation.

These results are summarized in a series of illustrations, for the several phenomena under discussion. Captions of the figures provide appropriate linkage to the text. It is of particular interest, in relation to the formation of etchable tracks in dielectrics, to examine Figure 5, which compares the criterion of primary ionization to that of energy deposition as a function of ion energy. Over a limited energy interval, the two criteria may yield comparable results, depending on the precision of the data for those bombardments which form etchable tracks, but if these criteria are calibrated by bombardment with machine accelerated ions in the energy interval 1-10 MeV/amu, they must yield discrepant results at relativistic energies, in such a way that the energy depo-

sition criterion will identify a track formed by a relativistic particle as having a higher Z than the identification made by the primary ionization criterion. The results of a simple calculation made for the energy stored in the positive charge resident in the primary column after passage of a charged particle shows that the energy in the column is substantially less than that generally accepted to cause dislocations (Frenkel defects) in the medium. Another illustration of interest in this connection is shown in Figure 7, where the restricted energy loss in AgBr is compared to the cross section for grain formation in emulsion. From the shape of the curve it is clear that both the cross section and the restricted energy loss cannot be good criteria for describing grain formation in particle tracks.

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