Criterion for Registration in Dielectric Track Detectors

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Dielectric track detectors have a sharp threshold for track registration that depends on the atomic number and the energy of the bombarding particles. New data on track registration in muscovite mica, Lexan polycarbonate, and cellulose nitrate contradict the previously proposed empirical criterion that tracks are formed if the total rate of energy loss exceeds a critical value that is characteristic of the solid. In contrast, the *ion explosion spike* mechanism for track formation predicts that a solid will record tracks if the rate of primary ionization exceeds a critical rate for that solid. All the known experimental measurements are consistent with this criterion.

I. INTRODUCTION

DIELECTRIC track detectors—in which tracks of heavily ionizing particles can easily be revealed by a suitable chemical etch—are currently being used in several disciplines, including nuclear physics, geophysics, and cosmic-ray physics. The usefulness of these detectors depends primarily on their ability to register heavy-particle tracks without being affected by a dense background of less highly ionizing radiation that does not form tracks.[1]

For each dielectric detector it is necessary to establish which particles will produce etchable tracks (referred to hereafter merely as *tracks*) and which ones will not. Earlier work by the present authors led to an empirical criterion in terms of the energy loss rate of an ion moving through a solid.[2] Three different solids—muscovite mica, Lexan polycarbonate resin, and cellulose nitrate—were bombarded with heavy ions of various energies and masses. The data were consistent with the hypothesis that for each solid there exists a critical rate of energy loss $(dE/dx)_c$ such that particles losing energy more rapidly than this value produce continuous tracks with unit efficiency, while those depositing appreciably less energy per unit length produce no tracks.

Further data have shown the need for an improved criterion that is applicable over a wider energy range than the dE/dx criterion. For example, we have recently shown, in collaboration with others,[3] that relativistic iron nuclei do not give tracks in clear Nixon-Baldwin cellulose nitrate, though tracks were predicted by our previous dE/dx criterion. In this paper we present further track registration data for the detectors studied previously.[2] The major purpose of the paper is to show that a new criterion based on primary ionization is compatible with the known observations in dielectric detectors.

II. EXPERIMENTS ON TRACK REGISTRATION

Table I summarizes the new data on track registration, and Figs. 1(a), 2(a), and 3(a) show why the data are inconsistent with a dE/dx criterion. Both the old and the new data are plotted. The new, low-energy results show that, relative to the critical values of dE/dx deduced in the previous work,[2] tracks register in all three solids at energy loss rates which are below threshold. Further, the incorrect prediction is made that relativistic iron nuclei should form tracks in cellulose nitrate.

The etching conditions used in this work were somewhat different from those reported in Ref. 2. The normal

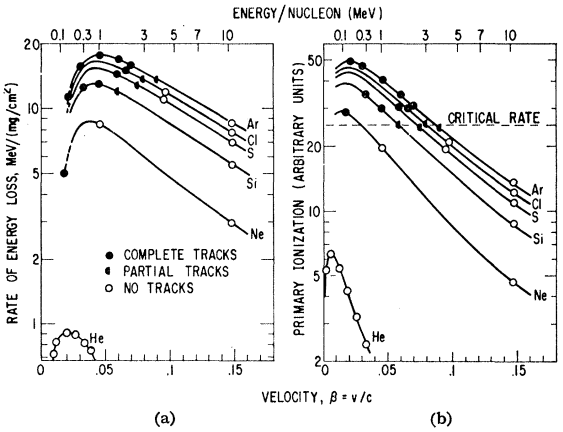

FIG. 1. Track-registration data as a function of energy for muscovite mica, plotted on graphs of (a) total energy loss rate and (b) primary ionization rate. The labels on the experimental points indicate for ions of various atomic number and velocity impinging on a mica surface whether etchable tracks are formed or not. The half-circle points signify that the registration efficiency is less than unity and increases somewhat with etching time. The data are inconsistent with a critical-energy-loss-rate criterion and are consistent with the existence of a critical rate of primary ionization for track formation, independent of charge and velocity.

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[1] The history, techniques, and applications of solid-state nuclear track detectors have been reviewed recently by R. L. Fleischer, P. B. Price, and R. M. Walker, Science **149**, 383 (1965); Ann. Rev. Nucl. Sci. **15**, 1 (1965).

[2] R. L. Fleischer, P. B. Price, R. M. Walker, and E. L. Hubbard, Phys. Rev. **133**, A1443 (1964).

[3] R. L. Fleischer, P. B. Price, R. M. Walker, R. C. Filz, M. W. Friedlander, R. S. Rajan, and A. S. Tamhane, Science **155**, 187 (1967).

etching time for muscovite mica is about 10 min in concentrated HF at 23°C. At the points in Fig. 1 denoted by filled half-circles, the tracks are so imperfectly developed after 10 min that they appear as pits less than 1 μ long. After an additional 60 min or more of etching, some of the pits lengthen into tapered tracks. At slightly lower energies, practically all of the pits grow into tracks after a long etching time. At slightly higher energies, all of the pits simply increase in diameter but remain very shallow ($\sim 1\,\mu$). For example, 161-MeV Cl ions give pits, about half of which lengthen into sizeable tracks after 60 min of etching.

Lexan is normally etched for about 10 min at 70°C in 6.25 N NaOH solution and then rinsed in hot water. This amount of time is sufficient to show whether the particles have left etchable tracks but is usually not long enough to etch the track to the end of the etchable range of the particle. As we will show in a subsequent publication, the rate of etching along a track in plastics is a function of the ionization rate of the particle, and

TABLE I. Track registration in various detectors.

Ion	Energy (MeV)	Registration efficiency[a]	Length (μ)	Reference
		Muscovite mica		
Ar^{40}	9	100%	~3	this work
Ar^{40}	16	100%	~4	this work
Si^{28}	14	100%	~3	this work
Ne^{20}	2 to 3	not known	>1	b
He^4	0 to 4.5	0	0	this work
		Lexan polycarbonate		
Cl^{35}	363	100%	long[c]	this work
Si^{28}	290	100%	long[c]	this work
Si^{28}	46	100%	long[c]	this work
Ne^{20}	207	0	0	this work
Ne^{20}	70	100%	long[c]	this work[d]
Ne^{20}	19.4	100%	long[c]	this work[d]
O^{16}	166	0	0	this work
O^{16}	88	0	0	this work[d]
O^{16}	15.5	100%	long[c]	this work
C^{12}	124	0	0	this work
C^{12}	25	100%	long[c]	this work
C^{12}	11.65	100%	long[c]	this work
He^4	~0.1 to 0.2	high	1 to 2	this work
		Cellulose nitrate (clear Nixon-Baldwin)		
He^4	3.2	low	~16	this work
He^4	2.5	100%	~12	this work
d	0.2	100%	~3	e
Fe	≥ 84000	0	0	f
$Z=11\pm1$	880	100%	>500	f
C^{12}	124	0	0	this work
C^{12}	100	100%	long[c]	this work
		Cellulose nitrate (orange Nixon-Baldwin)		
He^4	5.3	low	35	this work
He^4	4.0	100%	~24	this work

[a] In plastics the etching efficiency is less than the quoted figure when the angle of entry is very small.
[b] V. P. Perelygin, Joint Institute for Nuclear Research, Dubna, U.S.S.R. (private communication).
[c] Length of track increases with etching time up to a maximum value approximately equal to the range of the particle.
[d] We are pleased to acknowledge the aid of C. O'Ceallaigh, A. O'Sullivan, and D. Thompson.
[e] Reference 1.
[f] R. L. Fleischer, P. B. Price, R. M. Walker, R. C. Filz, M. W. Friedlander, R. S. Rajan, and A. S. Tamhane, Science 155, 187 (1967).

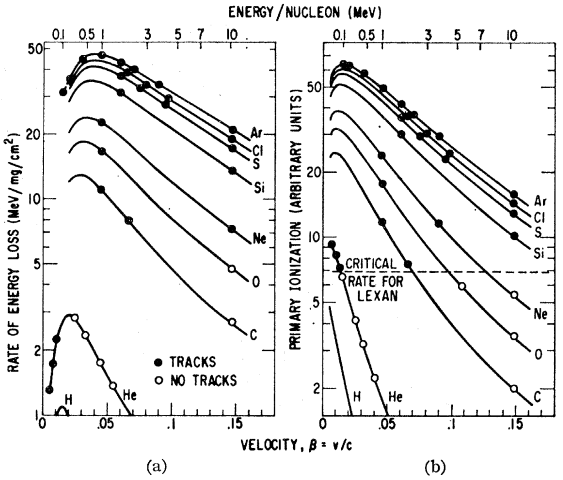

FIG. 2. Track-registration data for Lexan polycarbonate resin, plotted on graphs of (a) total energy loss rate versus energy and (b) primary ionization rate versus energy. The labels on the experimental points indicate for ions of various atomic number and velocity impinging on a Lexan surface whether etchable tracks are formed or not. The data are inconsistent with a critical-energy-loss-rate criterion and are consistent with the existence of a critical rate of primary ionization for track formation, independent of charge and velocity.

the track has a conical shape. For a lightly ionizing particle the cone angle is large, and a very long etching time, up to several hours, is necessary for full development.

Cellulose nitrate is developed in 6.25 N NaOH at 40°C for times ranging from about 5–30 min, depending on the variety of cellulose nitrate used. As is the case with Lexan, a longer etching time is necessary for full development of tracks of lightly ionizing particles.

III. THE PRIMARY IONIZATION CRITERION FOR TRACK REGISTRATION

We have recently developed a semiquantitative model of track formation which makes specific and correct predictions as to which solids should allow track formation and what the sequence in sensitivities should be among track-storing solids.[4] It gives a plausible description of the process that leads to a linear region of high chemical reactivity. This model notes that ionization by the track-forming particle creates a narrow cylinder of material with a net positive charge. The mutual Coulomb repulsion of the ions making up this region subsequently produces catastrophic atomic displacements leading to a dense cloud of interstitial atoms and vacancies along the original particle trajectory. This *ion explosion spike* mechanism predicts that a quantity somewhat different from (dE/dx) should determine the presence or absence of tracks: the number of ions formed per unit distance along the particle path. This quantity, called dJ/dx—the primary specific ionization—was

[4] R. L. Fleischer, P. B. Price, and R. M. Walker, J. Appl. Phys. 36, 3645 (1965).

calculated some years ago by Bethe[5]:

$$\frac{dJ}{dx}=(\alpha Z_e^2/I_0\beta^2)[\ln\{2mc^2\beta^2/(1-\beta^2)I_0\}-\beta^2+3.04], \quad (1)$$

where Z_e is the effective charge of the ionizing particle, β is the ratio of its velocity to c, the velocity of light, m is the electron mass, I_0 is the ionization energy of the outer electron of the material, and α is a constant that depends on the material. An empirical expression[6] for the effective charge, $Z_e=Z[1-\exp(-125\beta/Z^{2/3})]$, can be safely used down to velocities $\beta\approx 0.25\times 10^{-2}Z^{2/3}$ in calculating primary ionization curves for ions of atomic number 2 to ~ 20.

In polymeric solids less energy is required to break chemical bonds than to ionize atoms, and we have noted[4] that a high density of broken bonds along the trajectory of a particle effectively decreases the average molecular weight of this region and results in an increased chemical reactivity.

It is important to note that not all ionization or bond breaking is included in (1). The secondary ionization produced by delta rays generally occurs to the side of the main particle track and, according to the ion explosion spike model, is largely irrelevant to its formation. In fact, the major difference between the ionization and energy loss criteria is due to the increasing average energy carried off by ejected electrons at higher energies of the ionizing particle. From the ion spike model we expect that only the number (not the energy) of removed electrons is of importance as long as the electrons receive enough energy to drive them out of the track region. However, along the first few atom distances of their flight, delta rays can produce ionizations or broken bonds that may also contribute to track formation. The use of Eq. (1) as a description of track formation is intended primarily as a good working approximation which is justified by the finding that all of the presently available data in both organic (polymeric) and inorganic solids are consistent with the concept of a critical primary ionization rate for the track formation as calculated from Eq. (1).

In Figs. 1(b), 2(b), and 3(b), the new data in Table I and the old data in Ref. 2 are plotted on curves of dJ/dx versus β. For mica we used an outer-shell ionization potential of 13 eV; for Lexan and cellulose nitrate we treated I_0 as an adjustable parameter and found that small values of I_0 gave the best results. In order to calculate the curves in Figs. 2(b) and 3(b) we used $I_0=2$ eV, a value that is consistent with known bond-breaking energies.[7] One can see that for each solid it is possible to choose a critical value of the primary specific ionization above which tracks are formed and below which there is no preferential etching of the solid.

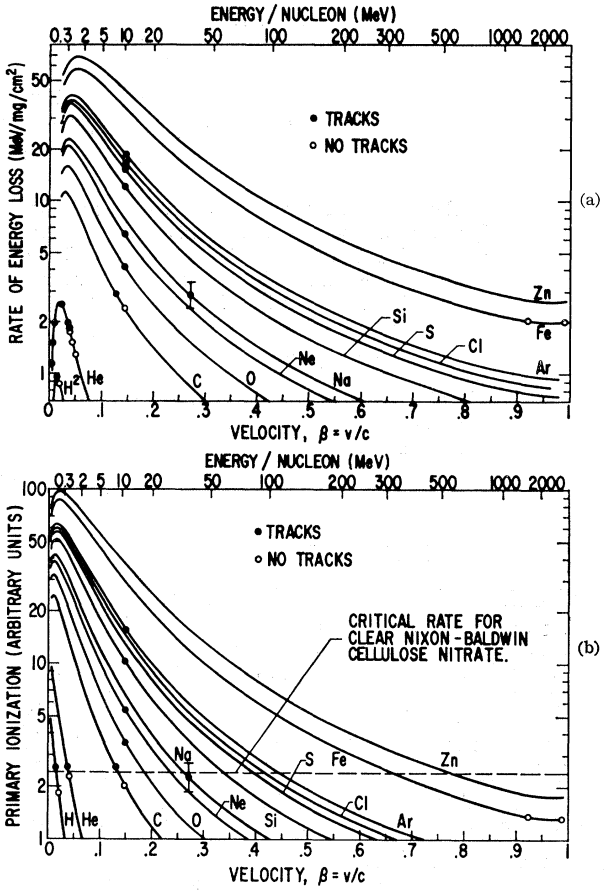

FIG. 3. Track-registration data for clear Nixon-Baldwin cellulose nitrate, plotted on graphs of (a) total energy loss rate versus energy, and (b) primary ionization rate versus energy. The data are inconsistent with a critical-energy-loss-rate criterion and are consistent with the existence of a critical rate of primary ionization for track formation, independent of charge and velocity.

IV. CONCLUSIONS

The available data on track registration do not yet provide a very stringent test of the new criterion. It is not unlikely that, as more observations are made of particles both at relativistic and at very low energies, the present criterion will have to be modified, either by adjusting I_0 or by devising a more realistic model that takes into account, in addition to the primary ionizations, higher-order ionizations that also contribute to track formation.

From the ionization criterion it is possible to infer how large a charge is necessary for registration of relativistic nuclei. The charges necessary for orange Nixon-Baldwin cellulose nitrate, clear Nixon-Baldwin cellulose nitrate, Lexan polycarbonate, and muscovite mica are $Z\geqslant 32$, 35, 60, and 130, respectively.

[5] H. A. Bethe, Ann. Physik **5**, 325 (1930).
[6] H. H. Heckman, B. L. Perkins, W. G. Simon, F. M. Smith, and W. M. Barkas, Phys. Rev. **117**, 544 (1960).
[7] F. A. Bovey, *The Effects of Ionizing Radiation on Natural and Synthetic High Polymers* (Interscience Publishers, Inc., New York, 1958), p. 16.