PHYSICAL REVIEW B VOLUME 32, NUMBER 8 15 OCTOBER 1985

Brief Reports

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Tracks of heavy ions in muscovite mica: Analysis of the rate of production of radiation defects

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(Received 13 February 1984; revised manuscript received 13 June 1985)

The rate of formation of extended defects by heavy energetic ions in track-forming minerals shows a pronounced nonlinear dependence on the linear ionization rate. It is suggested that the formation of an extended defect—as recorded by small-angle x-ray scattering—requires a certain threshold ionization density. As a consequence, the mean number of observable defects per ion track is related more directly to the fluctuation in ionization density than to its mean value.

Tracks of energetic ions, in particular, etched tracks in minerals, have been extensively studied after Price and Walker[1] developed a technique of fixing latent tracks by means of preferential etching.

The main interest of developing the study of latent and etched tracks in dielectrics was their identification as threshold detectors. It was then thought that this kind of material could be used as solid-state nuclear track detectors. Many calibration experiments were done in order to determine the threshold of registration for the different ions in various minerals.[2] It was then observed that in reality in such minerals as labradorite and mica (the most-used mineral detectors), for monoenergetic beams of incident ions, the distribution of lengths of their etched tracks is not a single function characteristic of a threshold of registration, but presents a width which depends on the etching conditions.[3] It was then shown that it is impossible to define a "total etchable range" for an incident ion of given atomic number in a mineral. This seemed to rule out the theories of etchable-track formation since they are all based on a threshold concept related to the mean energy loss or ionization rate of the incident ion.

On the other hand, the existence of a distribution in the lengths of etched tracks should be more easily explained with statistical considerations: Instead of the mean value of the energy loss or primary ionization rate, it is the fluctuations about this mean value which should be considered.[4,5] In the case of minerals, the accepted theory of track formation in minerals is the "ion-explosion-spike" theory of Fleischer, Price, and Walker[3] which covers the main characteristics of track registration in minerals. According to this theory, an etchable track will result if the rate of primary ionization of the incident ion exceeds a critical value dependent on the detector. Starting from this point, it is of interest to consider that the fluctuations of the ionization rate, rather than its mean value, are effective in creating etchable tracks of ions when their energy is in the critical region where the "registration threshold" was thought to exist.

Defects that make up latent tracks prior to etching have been studied[6-9] for ions with atomic numbers $7 \leqslant Z_1 \leqslant 36$ and energies E ranging from 1 to 8 MeV/amu by means of small-angle scattering of x rays. This covers the region of the "registration threshold" defined for muscovite mica and olivine. These measurements were linked with etching of the tracks of the same ions with the same energy. It was observed that the latent track in muscovite and olivine consists of extended defects with spherical symmetry linked by point defects.[8] After a very short etching time, $t = 15$ s, the defect contrast increases and the defects become cylindrical. It was concluded that the defects seen by small-angle x-ray scattering are lined up along the path of penetrating ions and are preferentially etched by the reagent.[9] The etchability of tracks was then linked to the linear density of the defects.

Experimental results on size, electronic density, and annealing behavior of such defects versus Z_1, as well as the rate of production of extended defects versus energy, have been reported.[2] These results are summarized in Table I which shows the mean diameter D of the spherical defects versus Z_1. It is seen from Table I that the diameter of the defects increases only slightly with atomic number Z_1. A similar conclusion is arrived at from alternative evaluations of the defect diameter.[7] Unlike the diameter, the mean number of defects is seen to vary quite drastically with Z_1 and E. This variation is much stronger than that of the pertinent cross sections for ionization, electronic or nuclear energy loss, as well as restricted energy loss.[3]

These observations, together with the fact that the mean

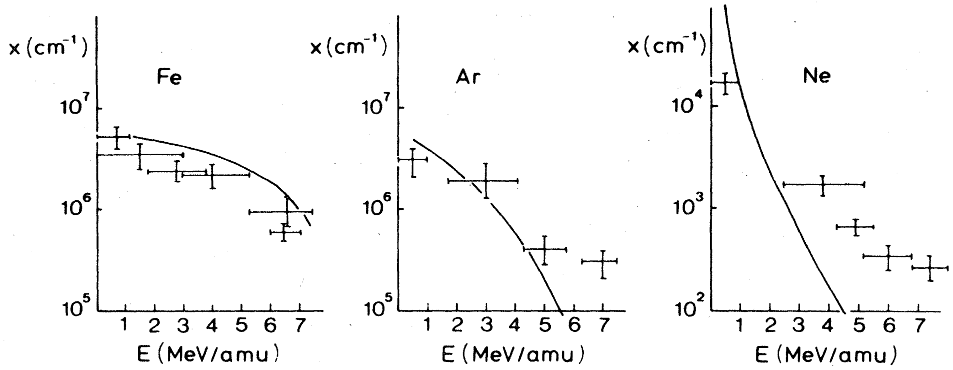

FIG. 1. Mean number of extended defects per unit track length x for Fe, Ar, and Ne ions incident on mica at initial energy E. Solid lines: Eq. (4).

rate of ionization is quite high (~ 1 event/Å), suggest a mechanism of defect creation based on the fluctuations of the ionization rate rather than the mean rate. In such a model, extended defects are created only in regions of exceptionally high ionization. Except for the different view at the microstructure of the individual track, this picture is compatible with any mechanism that produces observable damage by way of high-density (primary or secondary) ionization.[10-14]

Let r be the mean number of pertinent ionization events per unit track length. In the case of statistical independence, the probability $W(m)$ for m events to occur on a track element of length l is given by the Poisson distribution,

$$W(m)=e^{-rl}(rl)^m/m!\ , \tag{1}$$

and the probability for at least m events on l is

$$U(m_c)=\sum_{m=m_c}^{\infty} W(m)\ . \tag{2}$$

Thus, the mean number per unit track length of track elements of length l with a linear ionization density exceeding a critical value $r_c=m_c/l$ is given by

$$x=U(m_c)/l\ , \tag{3}$$

provided that $U(m_c) \ll 1$.

As a first attempt to evaluate the implications of this model, we keep the track-length element l fixed, i.e., independent of ion type and energy, and of the order of the defect diameter D. This implies that m_c must also be kept constant for a given material. Then, the density of damage zones along the track,

$$x=\frac{1}{l}e^{-rl}\sum_{m=m_c}^{\infty}(rl)^m m!\ , \tag{4}$$

depends only on the ionization density r, and its variation with r is determined by the expression

$$\frac{dx}{dr}=e^{-rl}(rl)^{m_c-1}/(m_c-1)!\ . \tag{5}$$

TABLE I. Mean diameter D of defects (full width at half maximum) observed at 1 MeV/amu by small-angle x-ray scattering in muscovite (Ref. 9), based on the assumption of a Gaussian distribution of the electron density in the defect.

Ion	Z_1	D (Å)
N	7	< 16
Ne	10	16
Ar	20	22
Fe	26	26
Kr	36	> 26

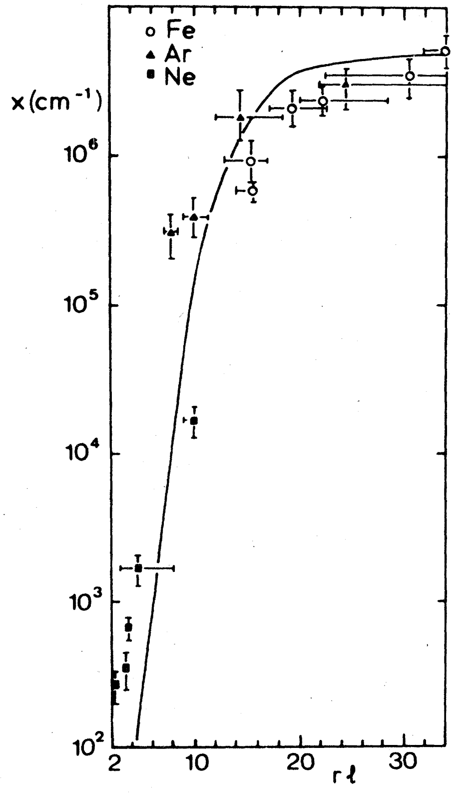

FIG. 2. Same as Fig. 1 with rl as the abscissa to demonstrate the scaling behavior predicted by Eq. (4).

In case of a high ionization rate or $rl >> 1$, an observed rapid increase of x with increasing r thus indicates that m_c must be very much greater than 1.

Figure 1 shows a comparison of the measured values of x with Eq. (4), for $m_c = 17$, $l = 20$ Å. r was calculated assuming $r = n\sigma$, with n the number of electrons per unit volume, σ the ionization cross section estimated from simple Coulomb interaction,

$$\sigma \sim \frac{2\pi Z^{*2} e^4}{m v^2} \frac{1}{I_s} , \qquad (6)$$

m and e the electron mass and charge, v the ion velocity, I_s a mean ionization potential which has been set equal to $I_s = 91$ eV for a mean atomic number $Z = 8$ of the target,[15] and Z^* a velocity-dependent effective charge number.[16,17]

The value of m has been chosen to fit the calculated x to the experimental point at $E = 1$ MeV/amu for Fe ions. It is seen that good overall agreement is obtained for the energy dependence of x, especially for Fe ions.

The data have been replotted in Fig. 2 in order to test the dependence of the defect-production rate x on rl, as predicted by Eq. (4). From Fig. 2, the following conclusions can be drawn:

(1) The three sets of data following from Ne-, Ar- and Fe-ion bombardment show a scaling behavior such that the defect-production rate is a function of the ionization rate r.

(2) This function deviates drastically from linearity.

(3) Within the accuracy of the scaling, the empirical function agrees well with the prediction Eq. (4), with parameters as indicated.

(4) The precision of the experimental data does not allow us to choose between "energy loss," "restricted energy loss," or "primary ionization rate" as the relevant parameter for creating the defects, since all these parameters do not have a different variation with energy, and it is possible to replace r by one of them and fit the data as well. However, these statistical calculations should be included in considering any of these models. The notion of "threshold," which is now in contradiction with experimental data, should be replaced by the "rapid variation of the rate of occurrence of fluctuations about a mean value."

This work was started when one of us (P.S.) was a visiting scientist at Orsay. The hospitality and interest of the group, especially H. Bernas and M. Maurette, are gratefully acknowledged.

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[1] P. B. Price and R. M. Walker, J. Appl. Phys. **33**, 3407 (1962).

[2] E. Dartyge, J. P. Duraud, Y. Langevin, and M. Maurette, Phys. Rev. B **23**, 5213 (1981).

[3] R. L. Fleischer, P. B. Price, and R. M. Walker, *Nuclear Tracks in Solids* (University of California, Berkeley, 1975).

[4] H. Dertinger and H. Jung, *Molecular Radiation Biology* (Springer, Berlin, 1970).

[5] A. Hedin, P. Håkansson, B. Sundqvist, and R. E. Johnson, Phys. Rev. B **31**, 1780 (1985).

[6] E. Dartyge and M. L. Lambert, Radiat. Eff. **21**, 71 (1974).

[7] E. Dartyge, M. Lambert, and M. Maurette, J. Phys. (Paris) **37**, 939 (1976).

[8] M. Lambert, A. M. Levelut, M. Maurette, and H. Heckmann, Radiat. Eff. **3**, 155 (1970).

[9] E. Dartyge, J. Phys. (Paris) **39**, 1287 (1978); E. Dartyge, doctoral thesis, Université de Paris-Sud, 1979 (unpublished).

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

[11] R. Katz and J. Kobetich, Phys. Rev. **170**, 401 (1968).

[12] H. G. Paretzke, in *Solid State Nuclear Track Detectors,* edited by F. Granzer *et al.* (Pergamon, New York, 1977), Vol. 1, p. 87.

[13] R. H. Ritchie and C. Claussen, Nucl. Instrum. Methods **198**, 133 (1982).

[14] T. A. Tombrello, C. R. Wie, N. Itoh, and T. Nakayama, Phys. Lett. **100A**, 42 (1984); T. A. Tombrello, Nucl. Instrum. Methods B **2**, 555 (1984).

[15] U. Fano, Annu. Rev. Nucl. Sci. **13**, 1 (1963).

[16] P. Sigmund, in *Radiation Damage Processes in Materials,* edited by C. H. S. Dupuy (Noordhoff, Leyden, 1975), p. 3.

[17] L. C. Northcliffe and R. F. Schilling, Nucl. Data Tables **7**, 233 (1979).