ELECTRON MICROSCOPE OBSERVATION OF ETCHED TRACKS FROM SPALLATION RECOILS IN MICA

P. B. Price and R. M. Walker

General Electric Research Laboratory, Schenectady, New York

(Received February 12, 1962)

We report here electron microscope observations of tracks in mica resulting from recoil nuclei produced in spallation reactions of 3.0-Bev protons. The results show that it is possible to study recoil nuclei using the high spatial resolution of the electron microscope (~10 Å). In particular, it is possible to search for decay events, on a time scale shorter than previously possible. The results also show that it may be possible to observe "fossil" cosmic-ray events in natural minerals. The observations were made possible by a chemical etching treatment which provides a striking demonstration of localized radiation-induced corrosion.

Fission-fragment bombardment of mica produces tracks which can be seen by transmission electron microscopy.[1-3] The tracks in synthetic mica are sharp and stable, whereas tracks in natural micas fade during observation and are difficult to measure. The fading can be eliminated by etching the samples in HF prior to observation. The acid permeates the tracks and eats permanent channels in the mica (see Fig. 1). The etching also enhances the sensitivity of particle detection. For example, fission fragments near the end of their range (where their rate of energy loss is low) show tracks after etching, although prior to etching the tracks are unobservable.[3] Thus the net effect of the etching is to "develop" and "fix" the charged particle tracks. Details of the technique will be published elsewhere.

Two proton irradiations were made. In the first, a sample of natural muscovite was irradiated in air with $\sim 9\times10^{14}$ protons/cm^2. Prior to etching no tracks were observed. After etching there was a track density of $\sim 7\times10^7$/cm^2. In the second irradiation sandwiches consisting of metal foils (Cu, Ag, and U) enclosed by synthetic mica sheets (1.5×10^{-3} cm thick) were given a dose of $\sim 3\times10^{14}$ protons/cm^2. Samples taken from mica surfaces adjacent to and downstream from the metals gave the following track counts: Cu-7×10^7/cm^2 (see Fig. 2), Ag-1.8×10^8/cm^2, U-1.4×10^9/cm^2. Samples taken from mica surfaces not adjacent to the metals gave track densities of $\sim10^6$/cm^2. No tracks were observed in etched, unirradiated samples.

Recoiling spallation residues lose energy at a rate comparable to fission fragments and are present in sufficient number to account for the observed results. Since none of the other spallation products have such high rates of energy loss, the tracks are attributed to the recoil nuclei. Proton-induced fission events also contribute tracks and are partly responsible for the high track densities from the U foil. However, the recoil nuclei will predominate for the lighter elements. The Ag foil results are the easiest to analyze since they can be compared directly with emulsion data. Baker and Katcoff[4] give an average range of $\sim 4\ \mu$ for AgBr spallation residues. If the mass of the recoil is $\gtrsim 40$, the range-energy re-

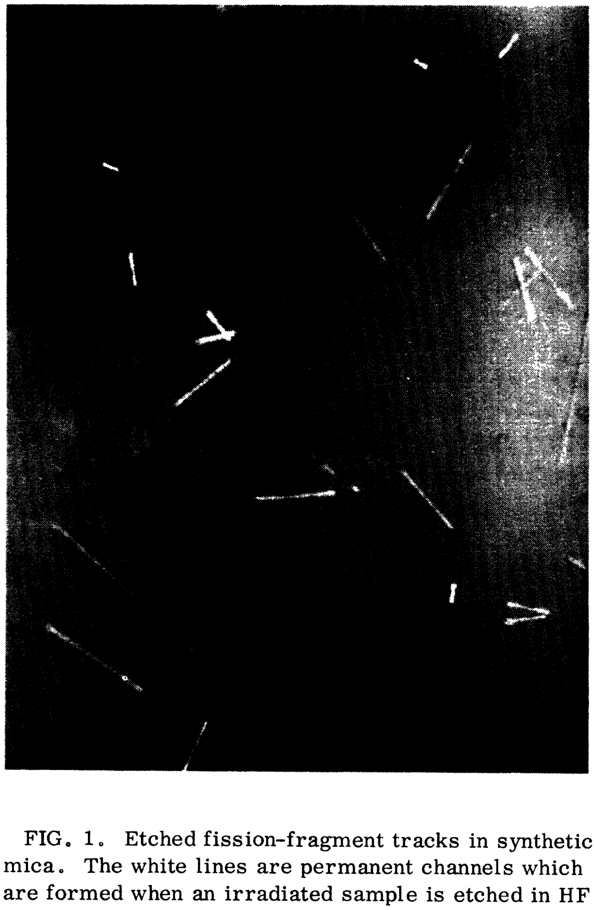

FIG. 1. Etched fission-fragment tracks in synthetic mica. The white lines are permanent channels which are formed when an irradiated sample is etched in HF. Although the etching rates are different, the technique works equally well for all types of micas.

FIG. 2. Recoil nuclei tracks in etched synthetic mica. The mica was immediately adjacent to a copper foil which was bombarded with $\sim 3\times10^{14}$ p/cm^2. Etch pits as well as continuous tracks are formed. The prominent bent track probably represents a scattering event.

sults of Heckman et al.[5] show that the rate of energy loss in mica is $dE/dx \gtrsim 1.5\times10^{10}$ ev/(g/cm^2). Fission fragments near the end of their range[6] have about the same dE/dx. If every recoil produced a visible track over its entire range, the track density should be $\sim 2\times10^9/\text{cm}^2$. The observed value is a factor of ten lower than this, which may be due in part to experimental difficulties such as dirty surfaces but probably implies that the efficiency for track production by recoil nuclei is less than unity. This is not unreasonable. As we will show below, light recoil nuclei ($M \sim 20$) do not contribute appreciably to the track densities. With heavier nuclei (and consequently higher energy loss rates), the formation of a continuous track will depend on fluctuations in the energy transfer. Sometimes a continuous path of damage will be produced, giving an etchable track, and sometimes the damage will be noncontinuous, giving rise to pits but not tracks upon etching (see Fig. 2). A systematic investigation of etching behavior using heavy-particle beams of known mass and energy is currently in progress.

Consider next the results for bulk mica, not close to a metal surface. Using measured ranges of spallation residues in light elements,[7,8] we calculate a recoil particle density of $\sim 5\times10^{-6}/\text{cm}^2$ per p/cm^2 in the bulk mica. The observed track densities of $\sim 8\times10^{-8}/\text{cm}^2$ per p/cm^2 (muscovite) and $\sim 4\times10^{-9}/\text{cm}^2$ per p/cm^2 (synthetic mica) are much less than this, indicating that only recoils of the heavier elements in the mica (e.g., Fe and K) contribute significantly to the track density. The difference between the muscovite and the synthetic mica is attributed to the presence of 1.5% of Fe in the natural crystal.

The present results show that it may be possible to observe "fossil" cosmic-ray events in natural minerals. We estimate, for example, that an extraterrestrial piece of mica which had been exposed to primary cosmic rays[9] for 3×10^4 yr would show an easily measurable recoil track density of $\sim 10^5/\text{cm}^2$. The maximum track density which could be resolved would correspond to an exposure of $>3\times10^9$ yr. Thus, this technique may prove useful for dating exposed minerals and may also give information about the history of the cosmic radiation. Unfortunately, mica is not found in meteorites, which are the only present source of extraterrestrial material. However, fission-fragment tracks have now been observed in a number of materials and track formation is probably a fairly general phenomenon. We are currently investigating meteoritic minerals for such fossil tracks.

We have assumed in the above calculation that the tracks do not fade. Synthetic mica is the only material in which a systematic study has been made of the thermal stability of tracks.[3] Here the tracks are retained until just below the normal decomposition temperature and hence are relatively permanent features of the crystal.

Some terrestrial micas may also show fossil tracks. One source of such tracks would be fission events from uranium impurities, which give rise to the well-known phenomenon of pleochroic halos.[10] Studies of these halos should give direct information on the fading of tracks over long periods of time. Star production by atmospheric cosmic rays[11] is another possible source of tracks. Assuming a set of extreme circumstances, namely, high-latitude surface exposure at an altitude of 3600 m, we estimate that an exposure of $\sim 10^5$ years would give a track density of $\sim 10^3/\text{cm}^2$. This would correspond to about one track per scan day and hence would be difficult to detect. However, the calculation was based on observations of one sample of Brazilian muscovite. Some micas contain over ten times as much Fe and may be correspondingly more sensitive.

The high spatial resolution of the electron microscope may make this method of track detection useful both for the study of short-time decay events and for studies of recoil nuclei in typical scattering experiments. The emission of a single nucleon of 10 Mev would sometimes give an observable kink in the track of a spallation recoil of mass 40. A kink occurring within 100 Å of the origin would be detectable and would correspond to a decay time of 10^{-15} sec. This is a long time for most nuclear processes but is shorter than has heretofore been possible to measure directly. The main advantage in scattering experiments would probably be the ability to measure angular distributions for near head-on collisions. The electron microscope detection of tracks will obviously become more useful when the sensitivity is increased to include lighter mass particles.

We would like to thank Dr. William H. Moore of the Brookhaven Cosmotron Staff for performing the proton irradiations. The assistance of Mrs. Ethel Fontanella in performing the experiments is also gratefully acknowledged.

---

[1] E. C. H. Silk and R. S. Barnes, Phil. Mag. 4, 970 (1959).

[2] G. Bonfiglioli, A. Ferro, and A. Mojoni, J. Appl. Phys. 32, 2499 (1961).

[3] R. M. Walker and P. B. Price, Bull. Am. Phys. Soc. 7, 52 (1962).

[4] E. W. Baker and S. Katcoff, Phys. Rev. 123, 642 (1961).

[5] H. H. Heckman, B. L. Perkins, W. G. Simon, F. M. Smith, and W. H. Barkas, Phys. Rev. 117, 544 (1960).

[6] C. B. Fulmer, Oak Ridge National Laboratory Report ORNL-2320 (unpublished).

[7] V. P. Crespo, thesis, University of California Radiation Laboratory Report UCRL-9683, 1961 (unpublished).

[8] A. M. Poskanzer (private communication).

[9] C. J. Waddington, Progress in Nuclear Physics (Butterworths-Springer, London, 1960), Vol. 8.

[10] For example, see E. Rutherford, J. Chadwick, and C. Ellis, Radiations from Radioactive Substances (Cambridge University Press, New York, 1930).

[11] G. Puppi and N. Dallaporta, Progress in Cosmic-Ray Physics, edited by J. G. Wilson (Interscience Publishers, Inc., New York, 1952), Vol. 1.

ELECTROMAGNETIC TRANSITIONS BETWEEN VECTOR MESONS

J. C. Taylor
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England

(Received February 5, 1962)

It has been remarked[1,2] that, owing to the closeness of the isoscalar 3-pion resonance,[3] ω, and the neutral isovector 2-pion resonance,[4] ρ^0, and their comparatively narrow widths, electromagnetic transitions between them might be important and lead to amplified violations of charge symmetry.

There is now evidence[5] that the ρ resonance can be resolved into two peaks, and that the higher of these, ρ_2, may be very close to the ω resonance indeed and have as small a half-width, probably less than 10 Mev. It is therefore possible that the $\rho_2{}^0$-ω transition effect might be very marked. It is the purpose of this Letter to provide a few more details than have been published by Glashow,[1] since they are now more likely to be relevant.

We shall assume that, in the vicinity of one of the resonances, the strong Hamiltonian is sufficiently described by the spectrum of states with the quantum numbers in question; and that this spectrum is well characterized by just the mass and width of the resonance. We then introduce electromagnetic interactions, and these will be significant if the transition amplitude between the isoscalar and isovector resonances is comparable with their separation and widths.

The amplitude, α, for electromagnetic $\rho_2{}^0$-ω transitions is presumably of the same order as electromagnetic mass differences, say 1 to 10 Mev. An estimate[2] of the contribution to α from the virtual process $\omega \to \gamma \to \rho_2{}^0$ gave a value of 2 or 3 Mev.[6]

Let $M_{S,V}$ and $\frac{1}{2}\Gamma_{S,V}$ be the mass and half-width of the isoscalar and isovector (ρ_2) states in the absence of electromagnetism. The states with a simple exponential time dependence, ψ_1 and ψ_2, come from diagonalizing the matrix

$$\begin{pmatrix} M_S-\frac{1}{2}i\Gamma_S & \alpha \\ \alpha & M_V-\frac{1}{2}i\Gamma_V \end{pmatrix}. \qquad (1)$$

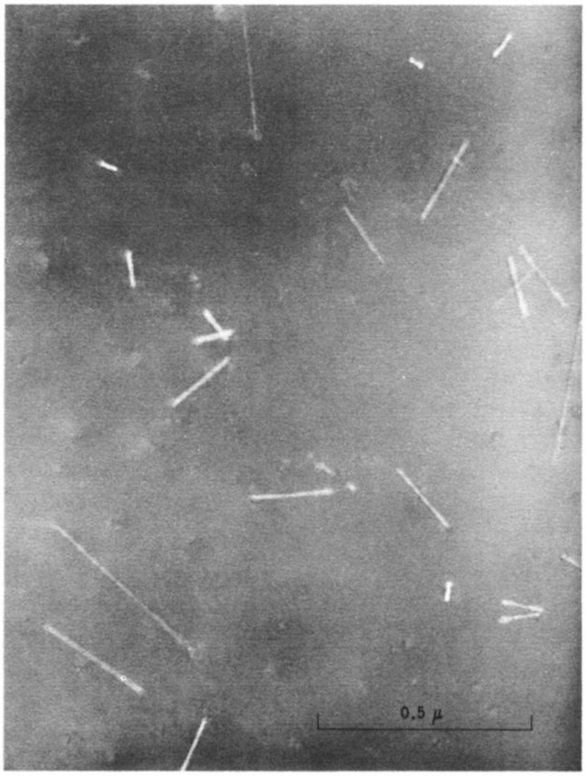

FIG. 1. Etched fission-fragment tracks in synthetic mica. The white lines are permanent channels which are formed when an irradiated sample is etched in HF. Although the etching rates are different, the technique works equally well for all types of micas.

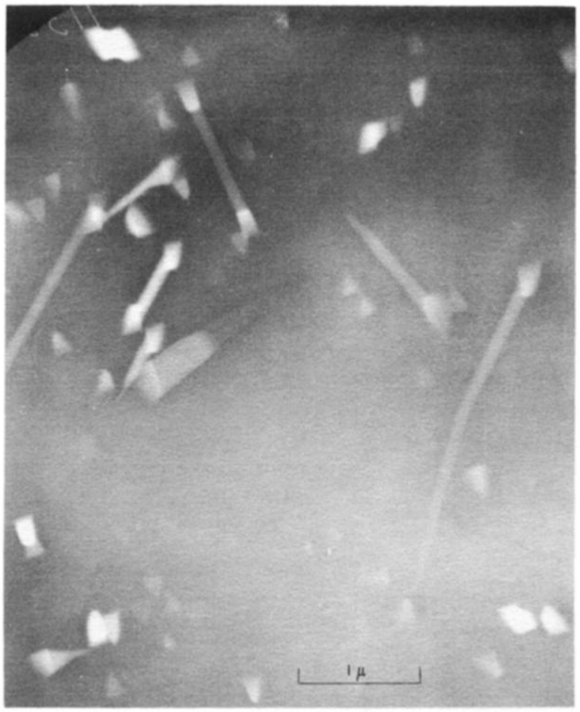

FIG. 2. Recoil nuclei tracks in etched synthetic mica. The mica was immediately adjacent to a copper foil which was bombarded with $\sim 3 \times 10^{14}$ p/cm^2. Etch pits as well as continuous tracks are formed. The prominent bent track probably represents a scattering event.