Chapter 1
Tracks in Mica, 50 Years Later: Review of Evidence for Recording the Tracks of Charged Particles and Mobile Lattice Excitations in Muscovite Mica

F. Michael Russell

Abstract Large crystals of the layered mineral muscovite mica often contain fossil tracks of charged positrons emitted from radioactive potassium atoms that make up 3 atomic % of mica. The tracks are made visible naturally by decoration with the black mineral magnetite coming from an impurity of iron that is precipitated after the crystals have formed deep underground. Positively charged high energy muon tracks created by cosmic rays also are recorded. The layered structure of mica allows thin transparent sheets to be peeled off to reveal a bewildering array of black lines, of which only 1 % are the tracks of charged particles. Lying mostly in random directions the charged particle tracks were identified in four years. The remaining 99 % of lines lying exactly parallel to chains of potassium atoms defied explanation for another 25 years until evidence was found for them being caused by recoil of potassium nuclei following emission of positrons. It was proposed the recoils created mobile highly-localised, self-focussing, non-linear lattice excitation of the lattice, called quodons, involving only a few atoms with energies up to tens of eV. After 10 more years the existence of quodons was shown in a laboratory experiment, confirming their stability against thermal motions of atoms. 10 years later, it was shown that atomic cascades, created by energetic nuclear scattering of swift particles, generate atomic-size kink-pulses that can gain energy from the metastable mica lattice. These cascades give rise to fan-shaped patterns containing multiple parallel tracks called striae. The possibility that 'ultra-discrete kinks' might explain the striae is examined. These and similar energetic lattice excitations should assist in annealing radiation-induced defects in crystals. The lines in muscovite mica remain the only way to observe the flight and behaviour of these excitations and illustrate the remarkable properties of quasi-2-dimensional atomic structures.

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J.F.R. Archilla et al. (eds.), *Quodons in Mica*, Springer Series in Materials Science 221, DOI 10.1007/978-3-319-21045-2_1

1.1 Basic Facts

Muscovite mica is a common mineral that can grow to large sizes in pegmatite masses. These occur as magma intrusions in the surrounding rock near volcanic shafts. Large crystals of muscovite can only form under conditions of high temperature and pressure, typically about 600 °C and at least 5 km underground. Its ideal chemical formula is $K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$ but it can accommodate various atomic substitutions and interstitial impurities. It is relatively stable chemically and, as it is insoluble in water, crystals can be found by natural erosion of uplifted rocks at the Earth's surface. Nearly perfect crystals are transparent and colourless but these are relatively rare. Usually, large crystals have a brownish colour. The *layered structure* of the muscovite lattice gives the crystals unique properties. They grow as tabular plates with a hexagonal outline. An outstanding property of muscovite mica is its easy cleavage in to thin transparent sheets. The thin sheets are elastic, flexible and surprisingly strong in tension in the plane of the sheet. The easy cleavage is in the (001)-plane of *monatomic sheets of potassium atoms* and is due weak van der Waals' bonding. Most crystals of muscovite of *size larger than about* 100 mm × 100 mm contain many dark lines or ribbons lying exactly in the (001)-plane. This can be verified by observing the interference of light between the top of a ribbon and the top of the covering layer of clear mica. The lines are very *thin ribbons of the mineral magnetite*, Fe_3O_4. This can be verified easily with a small magnet because magnetite is magnetic. Although muscovite crystals have been known since prehistoric times the cause of these dark lines remained a puzzle. Each sheet shows a different pattern of lines. However, there is an underlying symmetry to these patterns, which was assumed to arise from the crystal lattice structure. Even as late as mid-twentieth century it was suggested (by people versed in solid-state physics) that they might be caused by crystal dislocations despite being many orders of magnitude bigger [8] than typical dislocations.

Most crystals of muscovite have defects, either created during their initial growth or induced afterwards. At the micro-scale, these range from atomic point lattice defects up to micron-size crystal dislocations. Leaching can occur at crystal edges leading to intrusive dendritic growths. Structural defects such as twinning and non-conformal grain boundaries at intergrowths are usually obvious. Major damage to crystals, however, usually occurs by mechanical forces acting on the crystals during their rise to the surface by uplift and erosion. The most annoying of these defects are gross fractures as they degrade both the commercial and scientific value of the crystals. However, even a study of such damaged regions was informative. It was noted that the dark lines do *not occur near fractures of a crystal unless the fracture occurred after the lines had formed*. This is shown if Fig. 1.1. Since fractures generate many dislocations the absence of lines in their vicinity clearly eliminates them as the cause of most of the lines.

Because the lines conduct electricity but clear mica is an excellent electrical insulator of commercial importance almost all mined crystals are split in to ≈1 mm thick sheets at the mine, which are then segregated according to the amount of 'staining' that is present, as the lines are called. It is for this reason that most researchers in

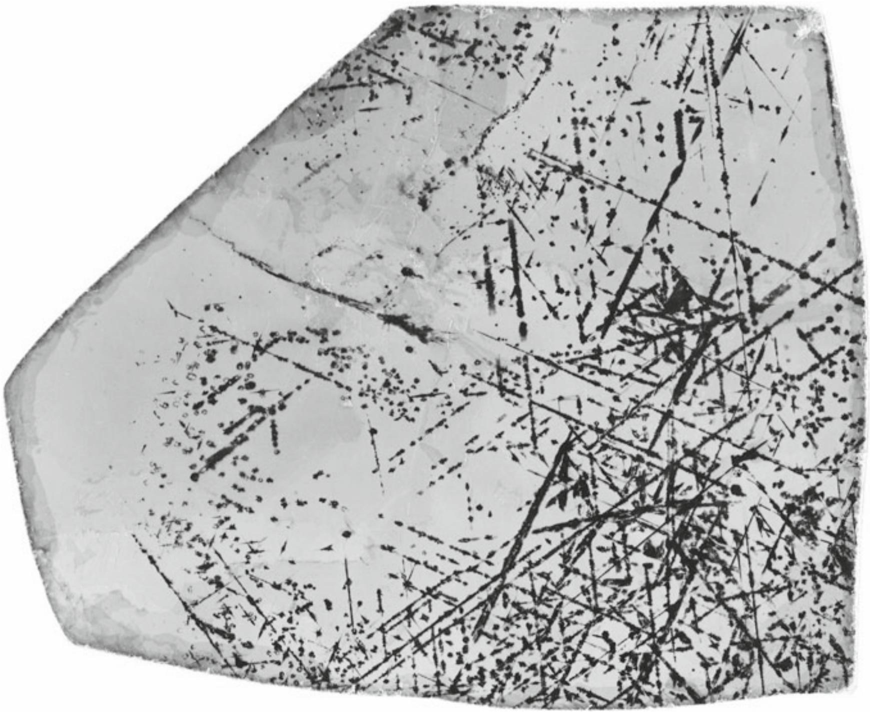

Fig. 1.1 Specimen of mica showing that the lines do not occur near fractures of a crystal unless the fracture occurred after the lines had formed

laboratories are unaware of the lines as only clear sheets are sold to or found in laboratories. This sorting also destroys the spatial relationships of the lines in different sheets. There is a great demand for muscovite mica as a filler in many compounds and mixtures, such as for cosmetics and paints. The chemical stability of muscovite and its exposure at ground level has led to crude mining practices, sometimes involving child labour. In the Jharkhand region of India, a major source of muscovite, despite tens of thousands of tons being produced annually the mining industry is cloaked in secrecy. As a result it is very difficult to purchase pristine crystals of muscovite, or even slabs, with well-defined lines that are suitable for scientific study. However, any quantity of random sheet mica can be purchased easily, characterized only by the area of the sheets and the amount of staining, quantified as clear, slight, moderate or heavy. The research described here is the result of studies of approximately 100 kg of randomly sorted sheets and slabs of muscovite showing more than a million lines of various kinds.

The lines can vary in width from about 1 micron to more than a millimetre. The thickness is variable in steps of the unit cell size of $\sim$0.9 nm of magnetite, being opaque after about 3 steps. Lines of narrow width tend to show only small variation of width along their length and thus allow more precise measurements of width, orientation and length. The wider lines appear to have developed by lateral accretion of material on initially narrow lines. The lines can have lengths ranging from a few millimetres up to the limit set by the size of the crystal, the largest of almost 1000 mm.

Visual examination of sheets with lines shows that the lines fall mainly in to two groups. Most lines lie in directions *parallel to the three main crystallographic directions at 60° intervals*, which is reflected in the hexagonal habit of the crystals. Lines in the other group lie mainly in *random directions in the* (001)*-plane*—with one exception. This relatively rare exception consists of multiple pseudo-lines, composed of linear arrays of small dots, which lie within a conical solid angle extending over many (001)-planes. These conical arrays cluster around the main crystal directions. In addition to the lines there are many dots of $\sim$1 mm diameter.

Initial studies of the lines showed that those lying exactly in atomic chain directions are *inconsistent with known crystal structure defects* such as dislocations, grain and twinning boundaries but were, nevertheless, clearly related to the crystal structure. The lines lying in random directions posed a serious problem as they had *no obvious cause and were not related to the crystal structure in the* (001)*-plane*. *A critical step was the presumption that all the lines and dots were the result of some kind of physical perturbation of the crystal and thus had a causal origin*. Prior to this point the lines were of unknown origin and sometimes were given metaphysical, even religious, attributes. When the present study of the lines started in 1963 the only known possible cause for producing the long lines lying in random directions in a crystal deep underground was high energy charged particles created by cosmic rays and neutrino interactions within the Earth. Prior to the discovery in 1936 of charged particles called muons in cosmic rays the randomly orientated lines in mica could not have been understood. This is an example of windows of opportunity for making discoveries. Another important window in the study of these lines was the discovery in 1960 [15, 16] that swift charged particles could penetrate further in certain directions in a crystal. This process is called channelling and is the result of the regular atomic structure of crystals. Surprisingly, the underlying principle of this process was foreseen by a thought experiment of Stark in 1912 [26].

1.2 Origin and Properties of Charged Particles in Mica Underground

There are only two sources of charged particles at the depth at which muscovite crystals grow and are able to record events. Local natural radioactivity, in both the crystal and the surrounding rock, and cosmic rays [9]. The relatively low energies involved in radioactivity limit the number of types of particles involved. They are alpha particles, electrons and positrons, gamma rays and rarely neutrons. Although only a few types of particles contribute to the primary cosmic radiation, mainly protons (99 %) and alpha particles (1 %), their great energies enable very complex interactions with the surrounding nuclei when penetrating through matter. In penetrating the atmosphere the most frequent nuclear interactions create kaons, pions, muons, gamma rays and neutrinos. The kaons and pions decay quickly so that muons are the dominant particles. The flux of muons decreases very rapidly with increasing depth in the ground due to the numerous nuclear interactions and ionization losses. This dependence on penetration depth effectively collimates the direct muons about the vertical direction. However, at the depths needed for crystal growth and recording a secondary source of muons then becomes important, namely from cosmic neutrino interactions. Neutrinos rarely interact with matter, can have very high energies, and cosmic neutrinos propagate in all directions. The paths of these secondary muons are essentially isotropic in space. Since crystals grow in random orientations to the vertical they discriminate against the direct vertical component in favour of the neutrino derived contribution [17]. At the $\sim$5 km depth required for recording tracks the flux of cosmic neutrino derived muons is comparable to that of the direct muons. The muons are mostly of high energy of order 10^3–10^4 MeV. As a result of the relativistic relation between energy and mass these behave as moderately heavy particles comparable to energetic protons. These were the most probable, although unlikely, deduced cause of the long random lines in muscovite crystals. In decreasing order of numbers there are additional small fluxes of neutrons, pions and protons due to nuclear local interactions of the muons near the crystals.

The other source of moderately energetic charged particles deep underground arises partly from radioactive elements such as uranium and thorium in the surrounding rock. Critical for the study of the lines, however, is the fortuitous fact that muscovite crystals contain a radioactive element, namely, potassium. In muscovite the isotope ^{40}K is radioactive, which occurs with an atomic abundance of 0.012 % and has a half-life of 1.2×10^9 years. In 1 cm^3 of muscovite there are $\sim$4 decays per second. There are three decay channels: 89 % give an ejected electron, 11 % is by electron capture by the nucleus with no ejected particle and 0.001 % gives an ejected positron. Thus in one year there are $\sim$1300 positrons and $\sim 1.3 \times 10^8$ electrons emitted from 1 cm^3 of muscovite mica. Both the electron and positron decays involve emission of a neutrino, the resulting energy spectra for positrons having a maximum of $\sim$0.5 MeV.

An unfortunate consequence of attempting cross-discipline studies, initially in isolation, is that errors can creep in to those studies which might not be detected for a long time. Such errors might arise from lack of knowledge or understanding of known data and from mistaken assumptions. In the study of the lines three such errors are known to have occurred. The first error occurred at the start of the studies when attempting to gain evidence for the longest lines being caused by muons. In analysing the data on the lack of straightness of the lines as evidence for random scattering of muons it was not realised that some of the lines being studied were caused by particles from an unknown source of lower energy.

The existence of an error was pointed out in 1967 but the authors did not find the cause [5]. The source of the error was found by Russell [19] in a few minutes when it was realised that an isotope of potassium in mica was radioactive. This finding opened a whole new field for study, because the decay process was well understood. Effectively, there was in each mica crystal an ongoing experiment that could serve for calibration purposes. The second error related to the recording process. Measurements on the dimensions of the lines gave the mass of the magnetite, and thus of iron precipitated, in any given sheet. In the absence of the iron impurity the recording process could not work so no tracks would be recorded. It was found that the length of the tracks of positrons from ^{40}K decreased as the volume density of iron increased. From this finding it was deduced that the positrons lost more energy to the iron impurity as the amount of iron increased. The simplest assumption was that the rate of loss of energy was proportional to the amount of iron present in the sheet. The validity of this assumption started to look suspicious in 2009 when studying the tracks left by supersonic lattice pulses created in atomic cascades. In 2013 Prof. G. Fitton measured the concentration of iron in six samples of mica which showed vastly different amounts of magnetite. He found that iron was present in all the samples at about the same high atomic concentration of $\sim$4 %. It now seems that the ability of mica to record tracks depends on the amount of iron present exceeding a minimum high value. The implications of this are still being studied. The third error related to the recoil kinetic energy of the potassium nucleus after emitting a positron. I did not properly understand the published data on the decay process and neglected to allow for the energy relating to the rest mass of a positron when emitted. This led to overestimating the kinetic energy of the recoil nucleus. Correcting this error showed that the recording process was even more sensitive than previously estimated. I am grateful to Prof. JFR. Archilla for pointing out this error in 2014 [2, 3, 12].

As determined by underground experiments, muons of average energy can have flight paths in rock of many metres. In an amorphous solid of the same composition as muscovite the maximum range of the electrons and positrons emitted in mica is $\sim$2 mm. However, the propagation of charged particles in crystals is greatly influenced by the lattice structure. In particular, channelling can extend the range of positively charged particles by a factor of $\sim$10 but not for electrons or other particles with negative charge. Hence, muons are the most probable cause of the long random lines with lengths greatly exceeding $\sim$20 mm. For lines in the range 2–20 mm the most probable causes are positrons or muons. All three decay channels cause a change in the charge of the nucleus. Positron emission leaves a negative charge, the other two channels leaving a net positive charge. As the recording process is charge sensitive this difference is reflected in the absence of additional decoration at the site of the decayed nucleus from which a positron track starts. The electron capture decay channel also can generate quodons.

All charged particles suffer elastic scattering as they propagate through any material causing their paths to deviate from a straight line. Fortunately, the form of the deviation from straightness is different for the expected muons and positrons because of their different masses and energies. Energetic muons penetrate much closer to a nucleus and experience the short-range strong nuclear force but the lower energy positrons experience only the long-range Coulomb force. It is the Coulomb force that gives the unique Rutherford scattering law. The short-range nuclear force gives point-like random scattering, known as a Gaussian distribution. Measurements on the long random lines showed that the scattering followed a Gaussian distribution as expected for high energy muons. For the shorter tracks, in the 2–20 mm range,

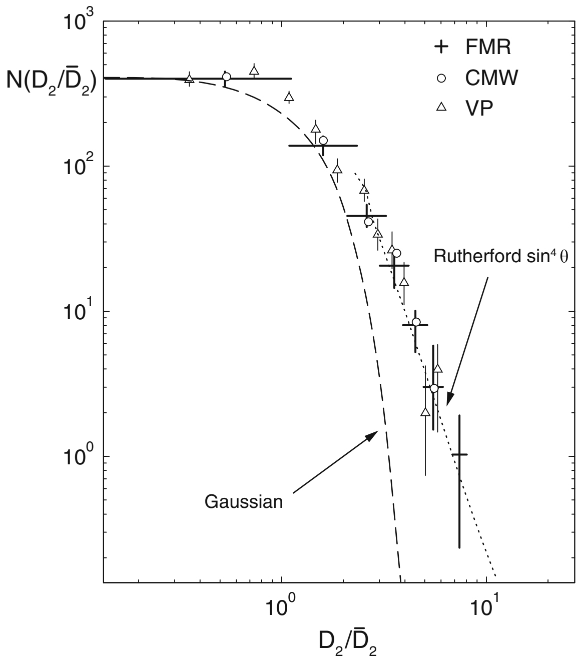

Fig. 1.2 Second difference of the deviations of paths of tracks <20 mm. A critical test for the lines to be the tracks of charged particles is how the lines deviate from straightness due to them being scattered as they pass through a solid. In the graph above the experimental results for the scattering of positrons in photographic film (△) clearly follows the Rutherford Law. Also shown are the results obtained by the author (+) and by Wolfendale's group (○). These results also fit closely to the Rutherford Law, thus strongly supporting the hypothesis that the lines are tracks of charged particles. Data from [5, 19, 28] for VP, CMW and FMR, respectively. Reproduced with permission from [19]. Copyright © 1988, Elsevier

measurements showed that some followed the Gaussian distribution as expected of muons. However, many followed the distinctive and unique Rutherford $\sin^4(\theta)$ scattering law characteristic of low energy positrons [28]. There is no known alternative cause for this unique scattering distribution. Because of the importance of this test for charged particles independent measurements of the scattering of the shorter lines were made that confirmed the result. The results of measurements on short tracks [19] (labelled FMR and CMW) in mica are shown in Fig. 1.2, together with those for positrons in photographic emulsions for comparison (labelled VP) [28]. This result provides unambiguous evidence that some of the lines are the tracks of relatively low energy charged leptons, either electrons or positrons; the relatively long range of $\gg$2 mm eliminates electrons, as their negative charge prevents them from channelling.

These scattering results did not identify in which layer of the lattice the tracks are recorded. Although the positrons are emitted from potassium atoms in the

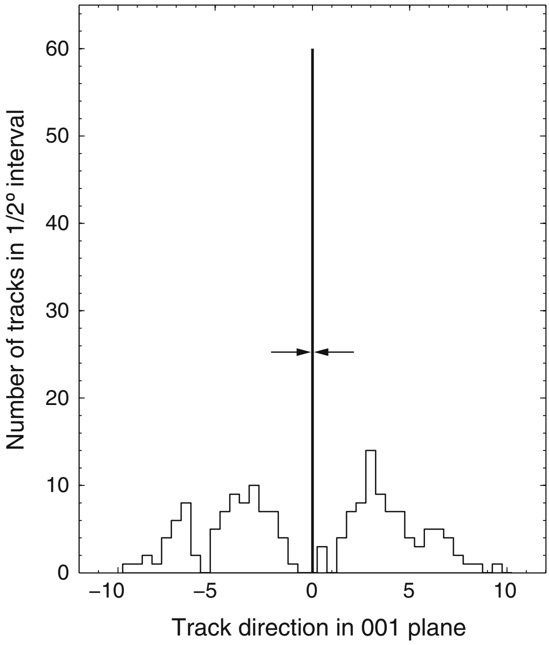

Fig. 1.3 Angular density of tracks showing the pattern of symmetrical diffraction peaks centered on a chain direction together with a strong peak of very narrow width exactly in the chain direction, see text. Reproduced with permission from [20]. Copyright © 1988, Elsevier

K-sheets they might scatter in to a different layer for recording. Fortunately, there is an unambiguous test for determining in which part of the lattice the positrons propagate and are recorded. Positrons are emitted isotropically from nuclei. In flight they interact with the surrounding lattice and the probability of their direction of propagation is determined by diffraction scattering by the lattice. If they propagated in the same K-sheet in which they were emitted then their angular distribution in the (001)-plane should show a unique pattern. This pattern consists of a strong peak of very narrow width exactly in a chain direction with symmetrical side peaks centred about the chain direction. The central narrow peak is evident in the results [20] shown in Fig. 1.3. This unique pattern is well known in optics for Fresnel diffraction of light by an opaque disc. For the positrons the positive charge of the nearby nucleus acts as the opaque disc. The angular distribution of swift charged particles incident on a crystal undergoing channelling shows only a broad peak in the channel direction.

The implications of this result are important. It shows that the recording process operates in the (001)-plane where the positrons are created, that is, in the vicinity of the sheets of potassium atoms. Since positron tracks can be recorded there is no reason that the tracks of positively charged muons should not also be recorded. The energy and momentum of the particles causing the long tracks can be found by measuring the extent of multiple scattering. Positive muons can channel, which influences the rate of scattering. Taking this in to account gave an energy spectrum of the particles that is consistent with independent studies of muons deep underground.

1.3 Measurement of the Sensitivity and Duration of Recording

The sensitivity of the recording process can be found by examining positron tracks. The observed longest length of a positron track lying exactly in a chain direction is slightly over 120 mm. If they were propagating by axial channelling then a maximum range of about 20 mm would be expected. The extended range is due to the open structure of the potassium sheet and diffraction scattering. The longest tracks will be caused by those approaching the maximum energy of 0.48 MeV. On the basis that the total amount of magnetite delineating a positron track from start to finish depends on the initial energy of the positron then the minimum rate of energy deposition per unit length of track can be found. This will be lowest at the start of the tracks when the positrons have highest energy and are moving fastest. Measurements showed that the threshold for recording a positron track was ~4 KeV/cm. That is, ~400 meV of energy per micron of flight path, or ~1 eV per 30,000 unit cells along a track. This is an astonishingly high apparent sensitivity. The energy needed to ionise an atom is typically of order 10 eV. If the recording process for positrons depended on creation of ionisation sites then the track would be delineated by ionisation sites at intervals averaging about 20 micron for the fastest part of the tracks. Measurements of the track widths of positrons show no evidence for such localised nucleation sites. This points to a recording process that depends on the transient presence of a positive charge as it propagates through the crystal. Since the recording process results in localised rearrangements of atomic structure of the lattice, giving rise to formation of the magnetite ribbons, it is likely that the recording process depends on local variations of crystal potentials, that is, chemical processes. This topic is examined further below.

The observed frequency of positron tracks per cubic centimetre of muscovite seldom exceeds 10 and often is below one. The rate of positron creation is about 1300 per cc of crystal per year. Clearly, the crystals cannot be continuously sensitive in time. This suggests that as they cool slowly after growth they become progressively more unstable internally and, at some time, start to record the tracks. If the recording process, once started, responded to all emitted positrons then, based on a yearly flux of ~1300 per cc, the recording process would operate for less than about three days to give the observed frequency of 10/cc. For lower frequencies the duration would be measured in hours. Assuming the recording process is of a chemical nature then the main variables would be the local pressure and temperature of the crystal. The tracks occur within crystals that have already grown and not during the growth stage. Evidence for this came from observation of the tracks left by electron-positron showers [18], which extend through many adjacent layers, whereas crystal growth occurs layer by layer. The geologically slow processes of rock uplift implies that the pressure changes only very slowly. Since the pegmatite intrusion is surrounded by a vast mass of rock the temperature of a given crystal also will change only very slowly. The change in these two variables would be exceeding small over a period of a few days. This leads to the conclusion only a very small fraction of the emitted positrons are recorded during the sensitive recording phase. This is not surprising since the recorded tracks all lie exactly in the (001)-plane, implying a very small solid angle of capture for recording. Estimation of the relative rate of capture is difficult because of the complexity of the lattice and unknown details of the recording process. Firstly there is the variation due to diffraction in the (001)-plane. Secondly, there is the shape of the positron energy spectrum giving few of high energy with long flight paths that are easy to recognise. Thirdly is the extremely small angle normal to the (001)-plane arising from diffraction, similar to that seen in the (001)-plane, in which they propagate. Based on reasonable estimates of these variables the probability for being recorded is in the range 10^{-5}–10^{-6}. The deduced recording durations are then of thousands of years. A period of a thousand years or so is compatible with significant changes in temperature of a large mass of rock. This extreme selectivity is most fortunate: if a much higher proportion were recorded it would be impossible to resolve them for study. In principle, the observed frequency of muon tracks allows an independent estimate to be made of the duration for recording. There is uncertainty of the muon flux in remote geologic times and of the efficiency for recording. If the flux was of similar order as now then the implied estimate for recording duration is compatible with that for positrons. We now turn to the origin of the majority of lines lying exactly in atomic chain directions that are inconsistent with tracks of known charged particles.

1.4 Interaction Between Theory and Experiment

A reasonable aim of research is to simplify, understand and explain the vast complexity of Nature. Theoretical concepts and techniques are vital tools in this quest, especially in attempting to make predictions that might be tested by experiment. But there are problems in attempting to cross disciplines and fuse concepts. The study of the lines in mica led to the concept of a new kind of lattice disturbance that could propagate through a crystal. It was given the name quodon. Attempts to fuse this concept with theoretical and computational work on the nonlinear behaviour of lattices pointed towards the concept of intrinsic localised modes, in particular, breathers and kinks. The problem is that these theoretical entities or concepts are well defined whereas their counterparts in Nature are not. A quodon seems to behave rather like a breather but not exactly. The cause of such difficulties often arises from the complexity of the actual experimental systems. For example, it is not possible to do experiments on isolated one-dimensional chains of atoms: they fall under gravity, fold, break and any attempt at measurements influences the chains. The concept of propagating kinks was introduced but what is measured or observed differs from the theoretical definition in various ways. So perhaps they should be called ‘kink-like lattice excitations’? Surprisingly, science manages to move forward despite these fuzzy and vague connections.

1.5 The Role of Atomic Chains in Propagation of Energy

In 1992 it was found that in certain crystals of muscovite containing some Ca the tracks of positrons delineated by magnetite were sometimes associated with long narrow ribbons of the mineral epidote. This has the formula $Ca_2(Al,Fe)_3(SiO_4)_3(OH)$. Each epidote line was aligned exactly in a chain direction and lay in the opposite direction to a positron track with which it was collinear and in the same layer [27]. TEM studies showed that the magnetite lines form as intrusions in the K-sheets that push apart the silicate layers but the epidote lines are thin compositional alterations of the lattice centred on the same K-sheet. Each ribbon of epidote had a constant width of about a micron that varied slightly for different ribbons. These pairs of lines occurred only for positrons of near maximum energy having long flight paths. The probability that the close association between these pairs of lines was due to random processes was negligible, especially as there was no explanation for what caused the lines of epidote. Hence, the action of emitting a positron from a nucleus was examined as a possible cause for the epidote lines.

The decay channel for positron emission involves a neutrino. The highest energy positrons occur when the neutrino carries away least energy. This means that the nucleus recoils in the opposite direction to the emitted positron. From the above analysis of positron tracks this means the direction of motion of the recoiling nucleus is close to a chain direction. This is reminiscent of energy transport as seen in Newton's Cradle but in the Cradle the masses are in direct contact. The maximum energy of the recoiling nucleus for positron emission is $\sim$10 eV, which means the atom is moving supersonically towards the next atom in the chain. It was logical to suppose that the epidote lines were caused by motion through the lattice of an entity or object carrying the recoil energy. For conciseness this object that moved along a quasi-one-dimensional chain was called a quodon. Analogue models of chains of atoms in a lattice resembling muscovite that interacted via nonlinear forces revealed a remarkably stable, highly localised, mobile excitation that propagated easily along chains. The duration of propagation was limited by only by frictional losses. This compact entity was found to be the only kind of excitation that could be generated by a swift impact. Numerical studies led by Prof. J.C. Eilbeck of a simplified model of a sheet of potassium atoms sandwiched between nearly rigid slabs of silica showed that quodons appeared to resemble a type of intrinsic localised mode of lattice excitations called breathers. This gave a useful model for investigating the chain-related lines [6, 11, 25, 29]. The main simplification involved in the numerical models was the assumption of a rigid framework of atoms surrounding the sheet of potassium atoms. This simplification introduced an on-site potential in the Hamiltonian describing the system.

The numerical studies showed that most of the energy in a breather was contained within a moving envelope of about ten atoms, with most of the energy held by atoms in the central chain. The atoms in a breather moved in an oscillatory fashion in the direction of the chain, adjacent pairs moving alternatively towards each other or further apart than the equilibrium spacing. The associated motion of atoms in adjacent chains was small, being negligible in chains further out. The motion of atoms within a breather show a phase velocity that exceeds the slightly subsonic speed of the group motion. Based on the assumption that a quodon resembles a breather the energy in a quodon apparently cannot exceed that of the originating recoil nucleus. Thus the maximum energy of individual atoms in a quodon could be a few eV. Atoms in a gas with this much energy would have a temperature of about 10^4 K. Hence, it is was considered plausible that the propagation of quodons could initiate atomic rearrangements of the lattice locally to catalyse the creation of epidote. Although the tracks of quodons were first identified in calcium rich crystals it was soon shown that the great majority of lines decorated with magnetite, which did not show charged particle-like properties, were due to quodons.

The dominant decay channel for ^{40}K is by emission of an electron. The maximum recoil energy of the nucleus in this case is $\sim$42 eV. As this is much greater than the recoil energy for positron emission most of the tracks attributed to quodons should arise from this source. This conclusion is compatible with the near absence of charged particle tracks at the end of quodon tracks in most crystals of muscovite, of high Fe but low Ca content, since the negative charge on electrons does not trigger the recording process. It is also consistent with the much higher frequency of occurrence of quodon tracks relative to that of positron created tracks. This fact remained a puzzle until the lower recoil energy for positron emission was pointed out by Archilla et al. [2]. Nevertheless, numerous examples were found of positron tracks with associated quodon tracks both decorated with magnetite. Figure 1.4 shows some examples.

There are several aspects of quodons that are poorly understood. Such as what fractions of the energy and momentum of a recoiling K nucleus are carried away by a quodon, relative to that radiated away as phonons. What determines the maximum energy a quodon might have? Is a quodon modified by the recording process? In particular, can it gain energy from the exothermic recording process? Since quodons can propagate further than 10^7 unit cells at room temperature in absence of possible energy gain from the recording process they must be essentially decoupled from the surrounding lattice. So how might they lose energy in flight in a perfect crystal? Not by generating phonons. Adjacent atoms within a quodon oscillate in nearly anti-phase longitudinal motion. If the internal motion was truly anti-phase then in the centre-of-mass system there would be no transfer of energy from one atom to the other, no matter how great the energy of both atoms. Departure from exactly anti-phase motion, however, does cause transfer of energy. A limit on this is set by ionization, that is, by raising the K atom of lowest energy to its next higher energy level. The first and second ionisation energies of potassium are about 4 and 31 eV, respectively. Assuming the potassium ions in mica are in their lower energy state then the *difference* in energies of the oscillating ions in a quodon cannot exceed 31 eV otherwise there will be loss of energy via ionization. This implies that the individual atoms could have greater energies than the difference value. Of course, the problem then is how might so much energy be coupled to a quodon to start with? In the case of quodon creation by a single recoiling nucleus the second ionization value might seem to limit the total energy coupled to the quodon. However, although ionization of the first atom by the recoiling nucleus would reduce the efficiency of kinetic energy

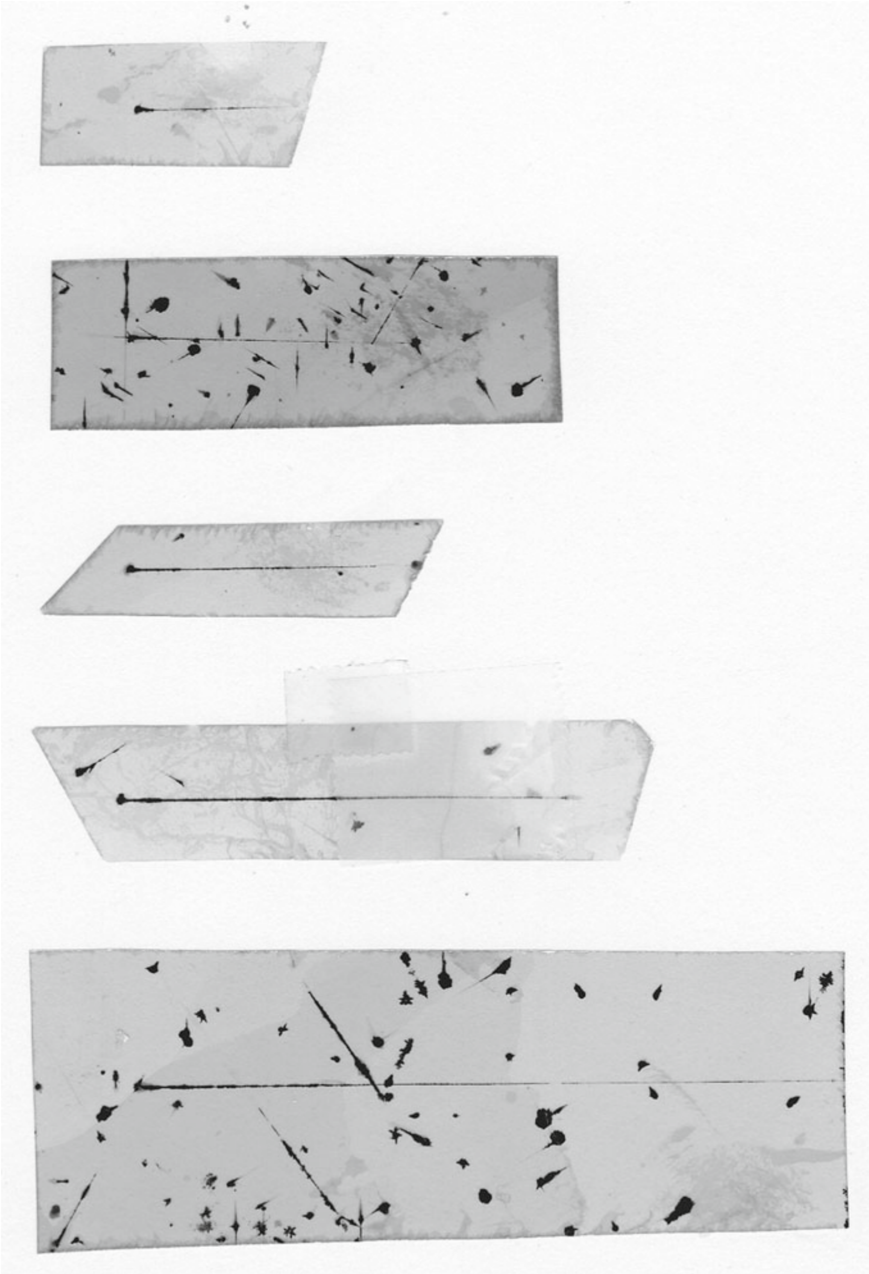

Fig. 1.4 Contact prints of positron tracks, showing the increase in width of a track as a positron slows down to give the characteristic tapered or tadpole shape. The maximum range of a 0.5 MeV positron in an amorphous material of the same atomic composition as muscovite mica is less than 2 mm. The large separation of atoms in the potassium layer and channelling both contribute to the extended range

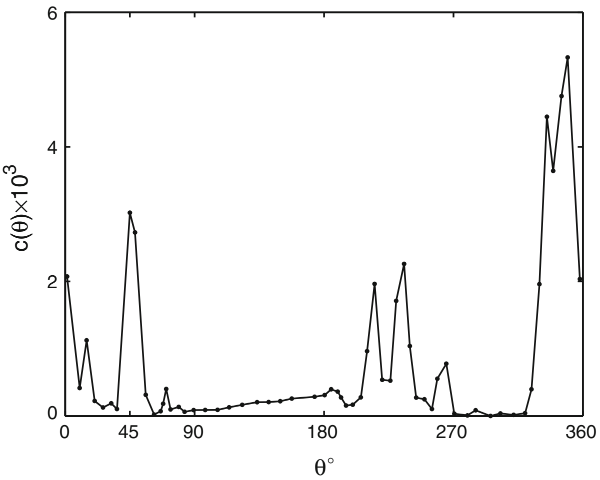

Fig. 1.5 Plot of the output from the channel plate detector as the crystal was rotated in front of the detector. A second source of alphas was attached to the crystal holder that could be brought to face the detector to test the detection and counting system. This source gave the peak labelled T. The crystal was then rotated to bring the bombarded edge to face the detector. Atoms sputtered from the bombarded edge and back scattered alphas gave the peaks labelled S. Further rotation brought the rear edge of the crystal to face the detector from which ejected atoms could reach the detector to give the peak labelled E [23]. See Russell and Eilbeck [23]

transfer the fact that it was ionized would not limit the kinetic energy it could couple to the quodon. The ionized atom would be left behind as the evolving quodon moved away.

1.6 Ejection of Atoms by Elastic Scattering of Quodons

Claims that natural crystals can permanently record, with astonishing sensitivity, transient motion of both high energy charged leptons and uncharged quodons calls for strong independent supporting evidence. One way would be to replicate in a laboratory the recording process in muscovite crystals. For a number of reasons this is still considered impractical. Simply re-heating under appropriate pressure a muscovite crystal showing lines to reverse the exothermic formation of magnetite and so restart the recording stage would not work. The entire initial lattice structure must be regenerated. However, the expected behaviour of breathers when they reach the end of a chain suggested a possible way forward [23].

By analogy with the decay of ^{40}K nuclei it was proposed that quodons would be created in a crystal of muscovite if it was bombarded with energetic alpha particles. Although the energy of the incident alphas from ^{241}Am ($\sim$5 MeV) greatly exceeded the recoil energy from ^{40}K the struck atoms would quickly loose energy by creating atomic cascades, giving atoms with energies in the 10–100 eV range. Some of these energetic atoms would collide with potassium atoms and create quodons. The quodons should then propagate along chains and on reaching the end of the chains at the opposite edge of the crystal *might cause ejection of the last atom from the chain*. To minimise the possibility of channelling of the alpha particles to the ejection face they were collimated so as to impinge on the crystal edge at near grazing angle. It was known that only about one in 10^4 of atoms ejected from a surface are ionised, so any ejected atoms were ionized by passing through a low intensity plasma. This was done so that the ejected atoms could be detected electronically by a channel plate detector. Appropriate electrostatic grids were used to prevent secondary electron emission and sputtering by field emission effects. It was found that atoms were ejected from the rear face of the crystal when the front face was irradiated with alphas and from a position on the rear face that was at the end of chains starting at the front irradiated spot. The results are shown in Fig. 1.5. The distance between the irradiated and ejection faces of the crystal was $\sim$7 mm or $>10^7$ unit cells. The experiment was done at room temperature. The interpretation of this experiment was that quodons created near the front face propagated along chains of $\sim 10^7$ atoms and still had sufficient energy to eject atoms from the crystal surface. Moreover, the experiment demonstrated that quodons were not destabilised by phonons at room temperature [23].

This experiment did not define uniquely the internal structure of a quodon. However, extensive numerical studies of possible lattice excitations have revealed the existence of only two types, namely, breathers and kinks. The structure of a breather and of a kink is illustrated in Fig. 1.6 for the simple case of a single chain in an array. A fundamental difference between breathers and kinks is that kinks are inherently laterally unstable in 2 and 3 dimensional systems but breathers can be stable in 2-D sheets, as shown in mica. Kinks in perfect lattices seldom propagate further than a hundred or so atoms along chains in 2-D sheets before degrading to phonons. For the above ejection experiment single crystals of high quality with little Fe content, as judged by their colour, were chosen to eliminate any possibility that the excitations

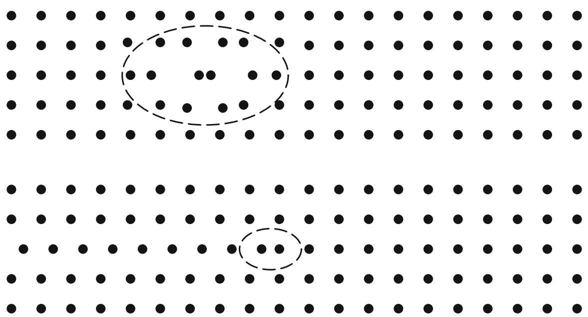

Fig. 1.6 The position of atoms in a chain of atoms in a crystal as two different types of nonlinear excitations pass along the chain. *Top* Breather. A breather can exist on a 1-dimensional chain and also in a 2-dimensional sheet. It is not known if they can exist in a 3-dimensional array like a metal. It is not known if multiple breathers can exist in close proximity. *Bottom* Kink. A kink is stable on a 1-D chain but is laterally unstable in a 2-D chain, spreading out and fading. Multiple kinks can be started in a sheet but spread sideways

might be driven by energy released via the exothermic recording process. The conclusion is that, in the particular case of muscovite, quodons created in the (001)-planes of K sheets most probably resemble breathers.

1.7 Thermal Stability of Lattice Excitations

The stability against thermal motions of atoms of the non-linear lattice excitations causing tracks in mica is remarkable. This is illustrated by quodon tracks of length at least 400 mm and kink-related tracks exceeding 120 mm. As this is a critical test of any proposed theoretical models for the excitations it is necessary to show that the tracks were recorded at high temperature. At present there is no known way to determine the actual temperature of a crystal when it recorded tracks. The tracks are themselves stable and remain unchanged by reheating in air to at least 1200 K. The observed occurrence of electron-positron shower tracks in many adjacent recording layers shows that the recording process starts after the crystal has grown. Another indicator of high temperature is the migration of iron and calcium to delineate the tracks. The Arrhenius' equation for rate of migration shows it depends exponentially on the reciprocal of absolute temperature. This points to high temperature. There are, however, two ways to set limits on the temperature. The first is by measuring the fraction of crystals showing fractures or gross deformations that occur before the recording process starts. If crystal damage occurs first then the local distortion of the lattice prevents propagation of quodons. In such crystals the damaged area is surrounded by a region devoid of any tracks. As large mica crystals grow, typically in molten granite, in a pegmatite intrusion there is competition for space with other crystals of various kinds, which could cause crystal damage. Once the pegmatite has frozen solid there will be little relative motion between adjacent crystals. So a mixture of damaged areas with or without tracks would restrict the recording stage to shortly after crystal growth. Measurements on the 100 kg of mica examined showed that more than 60 % of the damage occurred after the recording stage. On this basis the temperature during recording must be of order 900 K [7].

The second way to set a limit is to estimate the depth when recording occurred by determining the anisotropy of muon tracks. The muons created by neutrino interactions within the Earth are distributed isotopically but those penetrating directly from the atmosphere are strongly collimated about the zenith direction. The greater distance muons, incident on the ground away from the zenith, have to travel to reach a given depth leads to the collimation. The intensity in this collimated part varies approximately as $\cos^n(\Theta)$ where Θ is the angular departure from the zenith and n increases with depth but this relation fails at great depths. If a crystal is orientated during the recording stage so that the (001)-plane is near the zenith then there could be a grouping of tracks about one direction in the recording plane due to the direct vertical component. Unless the recording plane is aligned with the zenith there will be a reduction in the vertical component, which effectively narrows the half-width of the angular distribution. In practice, due to random orientation of crystals, less than 10 % of crystals might show evidence of collimation. Also, to establish an angular

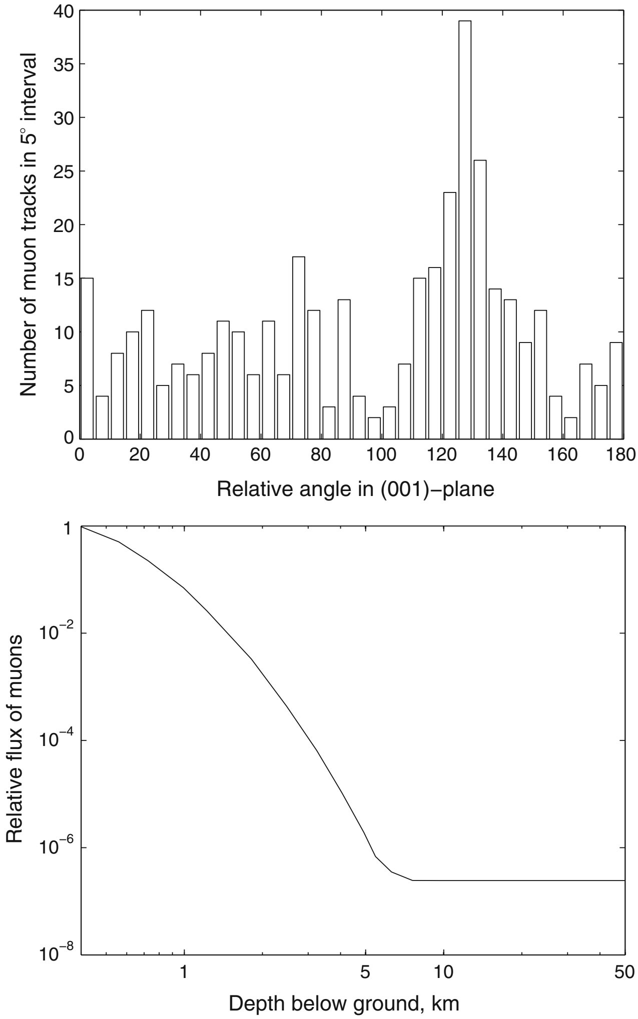

Fig. 1.7 *Top* Plot of the angular distribution of muon tracks in a 1 cm thick slab of muscovite mica. The plot shows both the random, isotopically distributed, muons created by neutrino interactions in the rock and the collimated direct muons created in the air. To record the direct muon component the slab must have been orientated with the (001)-plane lying near the zenith. *Bottom* Plot of the relative muon flux as a function of depth underground. At about 6 km the direct muon component falls below the neutrino created muon background. Since the plot in the *top figure* shows both the direct and isotropic components the recording must have occurred when the crystal was at a depth of at least 5 km. Data from [9] using that the density of granitic rock is 2.7 g/cc or, equivalently, that 1 km or rock is equivalent to 2.7 km water

correlation with crystal orientation thick slabs of a crystal are needed as random separate sheets scramble the orientation data. The angular distribution of muon tracks in one such crystal slab is shown in Fig. 1.7 (top). The grouping in the vicinity of 130° is statistically significant and suggests a depth in excess of 10 km. Another way to estimate the depth when recording occurs is by comparing the number of direct relative to isotropic muons that are recorded. For the data in the above figure this ratio is about 1/4. The actual dependence of muon intensity on depth is shown in Fig. 1.7 (bottom) from which it is seen that at depths greater than about 10 km the direct muons become negligible in number relative to the neutrino created ones. The conclusion is that the mobile lattice excitations must be recorded at great depths with temperatures approaching 1000 K. It should be remembered that the tracks are recorded at pressures in excess of 1000 bar.

1.8 Creation of Quodons by High Energy Particles

Some tracks of quodons consist of two parallel quodon tracks separated by a short section of track that is not in a chain direction [24]. Examples are shown in Fig. 1.8. The short sections of track show evidence of scattering and have random orientation in the (001)-plane, both characteristic of a charged particle. Since all three tracks are coplanar and joined at the intersections it is reasonable to suppose that the short tracks generate pairs of quodons. Positrons from K-decay have insufficient momentum to create quodons, which require movement of particles or atoms of much greater mass. The most probable candidates are pions or protons from high energy interactions of muons and neutrinos. Both have sufficient mass to create quodons. Although high energy neutrons also are present they are not able to trigger the recording process. The pions or protons will usually be propagating in random directions in the bulk mica and so not trigger the recording process. If they scatter off a potassium atom and then move in the (001)-plane the recoiling potassium atom could create a quodon. The second quodon would result by the inverse process when the pion or proton scatters out of the K-sheet and leaves no further track.

1.9 Nuclear Scattering of Muons

There is another test for the long lines lying in random directions being the tracks of muons in addition to the evidence for the expected multiple scattering. When an energetic muon that is propagating through a crystal scatters off a nucleus in or near a K-sheet it will transfer energy and momentum to that nucleus. If sufficient energy is transferred then an atomic cascade can develop. The initial motions of atoms in a cascade are hypo- then supersonic. This leads to the generation of multiple kinks and quodons, both of which propagate along atomic chains. But kinks are laterally unstable in 2 and 3 dimensional systems like the K-sheets. Instead of propagating like a quodon a kink spreads sideways to form a fan-shaped disturbance of the lattice in the K-sheet. As early as 1963 fan-shaped patterns were observed arising from the tracks of muons but at that time the existence and behaviour of kinks and quodons was not known. Recent numerical and analytical studies of kinks in 2-dimensional

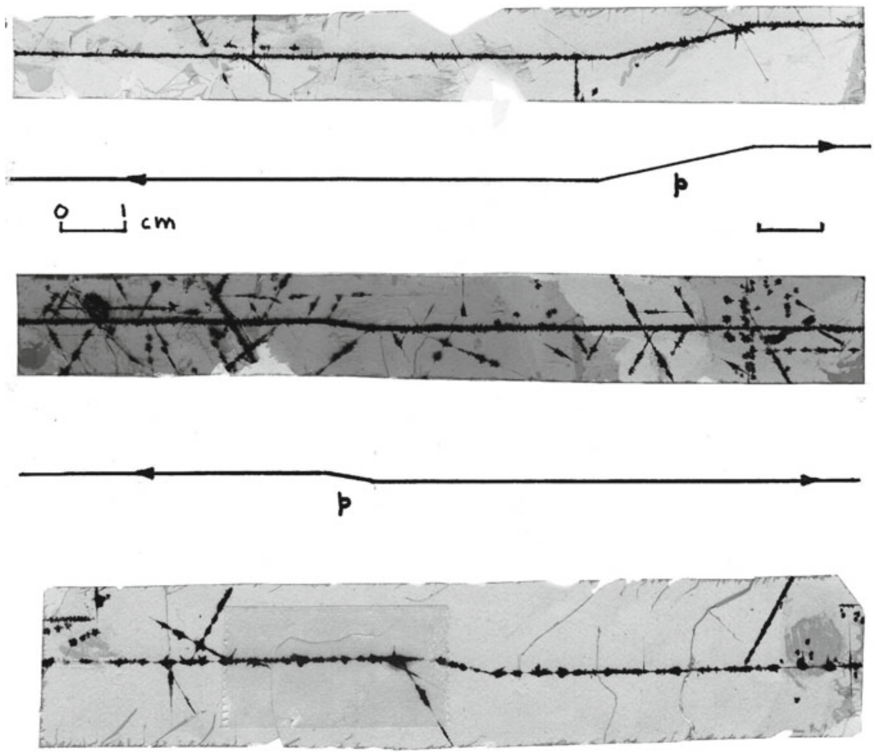

Fig. 1.8 Contact prints of pairs of quodon tracks joined by the track of a swift charged particle. One quodon is created when a particle scatters in to the recording layer. The particle leaves a track as it moves in a random non-atomic chain direction in the recording layer. The second quodon is created when the particle scatters out from the recording layer, creating the characteristic dog-leg pattern of two parallel quodon tracks joined by a section of track lying in a non-atomic chain direction. The short average lengths of the particle tracks creating these quodon pairs, compared to the average length of relativistic muon tracks, points to the swift particles being positively charged pions or protons. Pions, protons and also neutrons are created by nuclear interactions of the muons but the uncharged neutrons do not leave a track [24]

systems revealed a test for their existence, namely, the opening angle of the lateral spreading. This test was applied to the measurements made in 1963 and confirmed the existence of kinks in atomic cascades created by nuclear scattering of muons. However, there was a fundamental problem. The range of the observed fan-shaped patterns attributed to kinks were orders of magnitude to long. The energy of the kinks forming the fans should have dissipated after propagating over only a hundred or so atoms before degrading to phonons. The experimental evidence provided by the recorded patterns in mica implied that *somehow kinks were gaining energy as they propagated*. The only plausible possible source of energy that would be available to individual kinks in flight is that stored in the crystal lattice. In muscovite the energy is stored chemically and is released in the *exothermic* recording process.

This raised again the question of whether or not quodons could pick up energy in a similar way. The mica ejection experiment provided a partial answer because it showed that quodons could propagate $\sim 10^7$ atoms ($\sim$7 mm) in the absence of the recording process despite the crystals inevitably being contaminated with iron at a low concentration. The obvious stability of quodons in the layered structure of muscovite has not yet been demonstrated in any other non-layered crystal. Experiments on the 'long range effect' in irradiated copper can be interpreted using either quodons or kink-based fans if the latter can pick up energy from the lattice. It would be informative to study their possible creation and behaviour in simpler layered crystals by using the last atom ejection procedure. Fans hold the promise of providing a deeper understanding of transport phenomena in crystals because they can propagate in layered and non-layered crystals. Of special interest is their internal structure observed in muscovite. It looks like multiple kinks are forming, dying and reforming as the energy wave front propagates. Of course, a fundamental problem in studying the behaviour of these nonlinear lattice excitations is how to observe them in flight, especially in opaque materials.

1.10 Recording Process

As described above, there is much evidence to support the claim that positively charged particles can generate permanent tracks in iron-rich muscovite crystals. Moreover, there is strong supporting evidence, backed by experiment, for the creation of quodons that also can generate permanent tracks. However, quodons consist of localised nonlinear motions of atoms with no unpaired electrons or positive holes. If, following Ockham's Razor, it is assumed that the tracks of both charged particles and neutral quodons are recorded by the same process then that process cannot depend only on nucleation sites created by ionization. Since the recording process results in a chemical reordering of the lattice in the vicinity of the path taken by the mobile disturbance, be it a point-like positron or muon or a locally distributed quodon, then it must involve highly localised changes of crystal potentials. The absence of continuous tracks due to swift electrons and the lack of decoration due to a negatively charged atom following positron emission is indicative of a potential energy barrier inhibiting spontaneous precipitation of iron to form magnetite, even at temperatures exceeding 600 K. It is a logical extension that the recording process is initiated by transiently lowering a potential energy barrier locally.

There can be little doubt that the easy cleavage in the potassium (001)-plane, due to the weak van der Waals' bonding, and the large minimum separation between the potassium atoms in the same plane of $\sim$0.5 nm are important factors in the recording process. The formation of intrusive magnetite ribbons distorts the layered structure of a crystal. The bending of the layers in the vicinity of lines is visible to the unaided eye by observing sheets in reflected light. At the high hydrostatic pressures associated with a pegmatite this local distortion of the layers is accommodated in the bulk crystal by averaging the distortions over many layers. The energy released by migration of iron to form magnetite must be greater than that needed to distort the layers. The large separation between potassium atoms may well assist in the initial stage of the recording process when it is probable that only one ion moves in response to the transient disturbance caused by a moving particle or lattice excitation. The open spacing should also assist in the necessary subsequent migration of Fe and O ions in the (001)-plane needed to form the ribbons. It is probable that migration of ions normal to the silicate layers is difficult.

The concept of a potential energy barrier led to the idea that as crystals cool slowly after growth they enter a recording stage where the lattice tries to expel excess Fe and this is facilitated by the transient presence of a positive charge. The duration of this recording stage will depend on the concentration of Fe in the crystal at growth. It will also depend on the rate of cooling and the rate of migration of the Fe within the lattice. Further, it will depend on the rate at which Fe is removed from the lattice by accretion on tracks. If the tracks were of electrons the observed frequency of tracks would correspond to a recording duration time of minutes, which is unbelievable and totally at odds with the deduced times for positrons and muons. The absence of electron tracks implies that the recording process is inhibited by a local negative charge.

In the early stages of studying the lines it was assumed that the initial amount of iron held in a crystal was comparable with the amount precipitated in the magnetite ribbons. On this basis the recording process appeared not to function if the iron concentration was less than about one iron ion per 200 unit cells of muscovite. The relative positions of atoms in the muscovite lattice are illustrated in Fig. 1.9 [21]. The

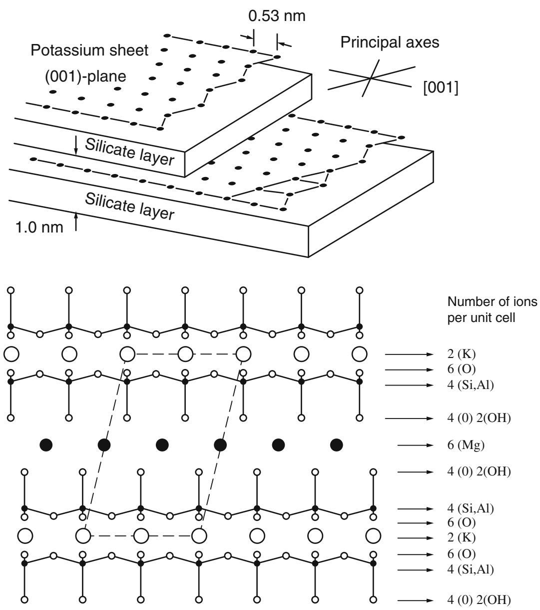

Fig. 1.9 *Top* Diagram showing the structure of muscovite. Iron can substitute for silicon in the sheets adjacent to the potassium sheets, so they will feel changes in crystal potentials caused by large amplitude motion of potassium atoms and passage of swift positively charged particles in K-sheets. *Bottom* Unit cell. Reproduced with permission from [21]. Copyright © 2014, Springer

maximum concentration was expected to occur when Fe^{+2} replaced the octahedrally coordinated aluminium, up to about two iron ions per unit cell. This suggests a maximum concentration of Fe of about 2 atomic %. Most samples of clear muscovite lie in the range from almost none to up to this value. In addition, Fe^{+3} can also replace silicon that, significantly, is closer to the potassium layer in which the positrons propagate. However, recent measurements of the Fe content in crystals showing good recording of tracks have shown that the concentration is almost constant at about 4 atomic %. The big surprise was that the amount of Fe differed little in regions of a sheet that showed many tracks from regions showing none. Estimates were then made of the amount of Fe held in the magnetite ribbons. It was found that the amount in the ribbons was minute in comparison with the bulk mica. This suggests that crystals that can record tracks must start with a surprisingly high iron content that will make the structure more strained than for crystals with low iron substitution. It is then perhaps not surprising that as such crystals cool they try to revert to a lower energy state by expelling excess iron in the form of staining. Since the staining does not occur at random there must exist an inhibiting potential energy barrier. The existence of the tracks shows that swift positively charged particles facilitate the rearrangement of atoms by lowering this potential energy barrier. Positrons lose energy as they propagate by scattering off interstitial impurities but this is not the cause of the tracks. This is because the average rate of energy loss per unit length of track for the fastest positrons is far too small to significantly influence the local chemical bonds. The close proximity of the moving positrons to the iron and oxygen in the silicate layers should be an advantage if the Fe^{+3} ions are involved. Probably the only way that details can be revealed of the movement of charges and atoms that occur in the recording process is by computer simulation. Although this model of the recording process provides a possible recording mechanism it does not give a complete description for the formation of the observed tracks.

1.11 Interactions of Mobile Lattice Excitations with Stored Energy

The only way that laterally unstable kink-pulses could propagate the great distances observed in muscovite crystals is by gaining energy from the exothermic recording process. This raises the question of how an atom of iron moves from one site, probably in a silicate layer, into the adjacent K-sheet where the recording process operates. Owing to the motions of atoms in a kink-pulse either the Fe ion is attracted to the space immediately in front of the pulse or to just behind it. In the compression front the K-atoms are closer together, which seems unlikely to create a potential well for a Fe ion to enter. In the immediate wake of the pulse, however, the K-atoms are more widely separated than in equilibrium conditions. This would create a transient potential well to receive the Fe ion. As soon as the Fe ion was in the well it would impede the recoiling motion of the two adjacent K-atoms, thereby driving the

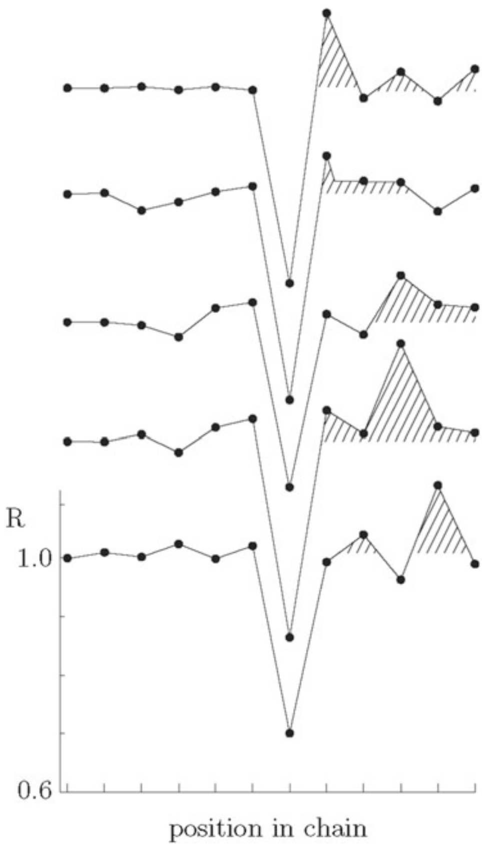

Fig. 1.10 Plots of the ratio of separation of potassium atoms relative to their equilibrium separation as a kink-like pulse moves along a chain of atoms. The different plots are for equal intervals of time for a single pulse on one chain. The *shaded parts* indicate where atoms are more widely spaced than normal. It is energetically unfavorable for an interstitial atom or a nearby atom to insert in to the chain when atoms are closer together than normal. See Russell [21]

kink-pulse forwards. The positions of atoms as a kink-pulse propagates has been studied by molecular dynamics. Figure 1.10 shows the variation of atomic spacing between adjacent atoms on a chain, expressed as the ratio of their instantaneous separation relative to their equilibrium separation. Each plot is a snapshot at equal intervals of time in a sequence as the kink-pulse moves to the left. They were derived for the much simpler case of a 2-D layer in a metal crystal, because of the complexity of studying the muscovite lattice. The restrictions on motion of atoms in chains in the K-layer are likely to be similar to those in a metal, so these results should give the general picture. In these plots the shaded regions are where the separations are greater than at equilibrium. An alternative to the chemical storage of energy in iron-rich muscovite is by irradiation to create interstitial ions and vacancies. The existence of fans of long range decorated with magnetite shows that some kinds of nonlinear lattice disturbances can pick up energy from a lattice. In a non-layered crystal they would propagate and expand within a conical envelope.

Examples of kink-pulses of long range that continuously gain energy are shown in Fig. 1.11. These are created by nuclear scattering of a swift heavy particle moving

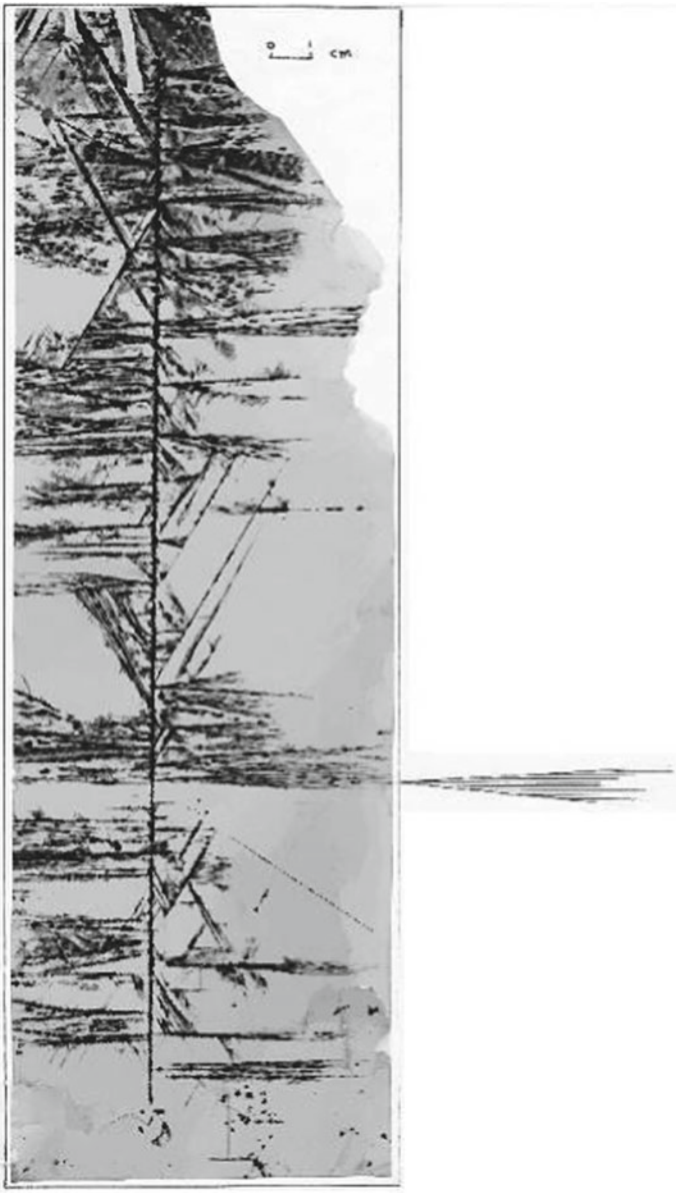

Fig. 1.11 Photograph showing the track of a heavy charged particle, moving in an axial channelling direction in the recording layer, undergoing multiple nuclear scattering events. Each scattering event produces an atomic cascade that creates kink-pulses, which develop in the two-dimensional recording layer as a fan-shaped pattern. The range of the fans shows that the kink-pulses must gain energy from the metastable lattice. The length of the primary track is 270 mm

in the vertical direction. Each one resembles a partially open hand fan. The existence of such fans raises the question as to whether the great range of quodons might also be due to energy gain from the recording process. By analogy with the situation in kink-pulses, the oscillatory internal motion of atoms in a quodon, giving repeated greater-than-equilibrium separations, would offer multiple potential wells. In contrast to kink-pulses, it is not obvious that insertion of ions into such wells would result in an overall increase in the energy of a quodon. This is due to there being several possible positions for insertion and some positions might impede the internal motions. It can be argued that insertion always adds energy to the excitation. Some of this energy will be incorporated into the quodon with the remainder radiated away as phonons. A possible outcome might be no net gain in energy. There is some evidence for this outcome. By scattering at a crystal defect a daughter quodon of lower energy can be created that propagates in a different chain direction. The probability for scattering of the daughter is increased because of the lower energy, leading to further quodons of progressively lower energy. After a few such scatterings this sequence stops. If quodons could gain energy then all the daughters might continue indefinitely, which is not observed.

1.12 Confined Lattice Excitations

It is logical to explore what might happen if a quodon or kink-pulse was created in a micro or nano-sized crystal that contained available stored energy. Suppose the binding energy of atoms in the crystal was high enough to prevent ejection of atoms by inelastic scattering. Then the excitation would be reflected when approaching any face. In effect it exists within a cavity. If the reflecting faces were perpendicular to the excitation flight path and there were no crystal defects then an excitation might approach an infinite life. In practice, the life would be shortened by imperfect reflections due to the internal stresses distorting the lattice in a nano-sized crystal. Some indication of the possible life of a quodon can be seen from the longest flight paths observed in large crystals, typically, $\sim$0.4 m. Assuming a quodon has the highest internal optical-mode oscillations with atomic spacing of $\sim$0.5 nm then an observed flight path of 0.4 m gives about 10^9 oscillations. An important question is how much energy such a quodon might absorb by annealing defects or removing stored energy in the lattice. Similar reasoning would apply to kink-pulse excitations. A current topic of interest is the possibility of releasing energy stored in a crystal at the nuclear level by fusing hydrogen with a heavy nucleus to change the isotopic ratios of the element. This might be achieved by repeated attempts at tunnelling by means of a confined or stationary ILM of some kind [10].

1.13 Internal Structure of Fans

There are several distinctive features of fans such as those shown in Fig. 1.11. Firstly, it is known that fans are generated by nuclear scattering of swift charged particles. The occurrence of two matching sides to each fan is inconsistent with the sides being the tracks of any known charged particle. In electron-positron pair production only the positively charged particle leaves a recorded track. Moreover, due to their small rest mass positrons do not create multiple lattice excitations. It follows that the fans must be produced by some kind of mobile, highly localised, lattice excitation. The tracks of the lattice excitation causing the sides bounding a fan do not lie in atomic chain directions. Therefore, the excitations cannot be quodons. Measurements of the full opening angle 2θ of fans show there is a minimum opening angle of about 2° consistent with the expected lateral expansion of supersonic kink-pulses in a 2-D sheet [21].

Secondly, the range of fans exceeds by several orders of magnitude that expected of kink-pulses created in atomic cascades. Their observed range is usually significantly less than that of quodons. In particular, in contrast with the behaviour of quodons, the range of fans depends on the amount of the iron impurity that is precipitated to record the passage of the kink-pulse disturbance [21]. The only way kink-pulses can propagate the great distances observed in mica is by gaining energy from the meta-stable lattice. The meta-stability arises from the structural reorganisation required to expel the iron from the lattice as a crystal cools.

Thirdly, a uniquely distinctive feature of fans is the occurrence of multiple parallel tracks lying within the defining side boundaries, called striae. These are clearly seen in the fans shown in Figs. 1.11 and 1.12. These striae are always parallel to the single atomic chain direction that lies within the angular width of a given fan. It is reasonable to assume that each track in the striae is the result of a localised excitation of the lattice propagating along a chain. Could these excitations be quodons? The available evidence does not support this possibility. The individual striae in a given fan all terminate at about the same distance from the fan source. If they were quodons then they would propagate at subsonic speed whereas the kink-pulse sides move at supersonic speed. Moreover, quodons would propagate individually and so have no correlation on their range. Again, in contrast with quodons, the striae never create secondary striae moving in a different chain direction as a result of scattering by a crystal defect. Tracks of individual striae can terminate and then seemingly reappear later further along a fan. Again, this is inconsistent with quodon behaviour.

Fourthly, the excitations causing the striae must be stable against strong thermal motion of atoms in the lattice at temperatures of order $\sim 500\,^\circ$C that pertain during the recording stage of mica. This is a critical requirement. Numerical modelling of atomic cascades in metals shows that kink-pulses, usually produced by specifying one atom has an instantaneous finite velocity, can propagate in absence of thermal motion and spread laterally [13, 14]. *In practice, atoms gain energy over a finite*

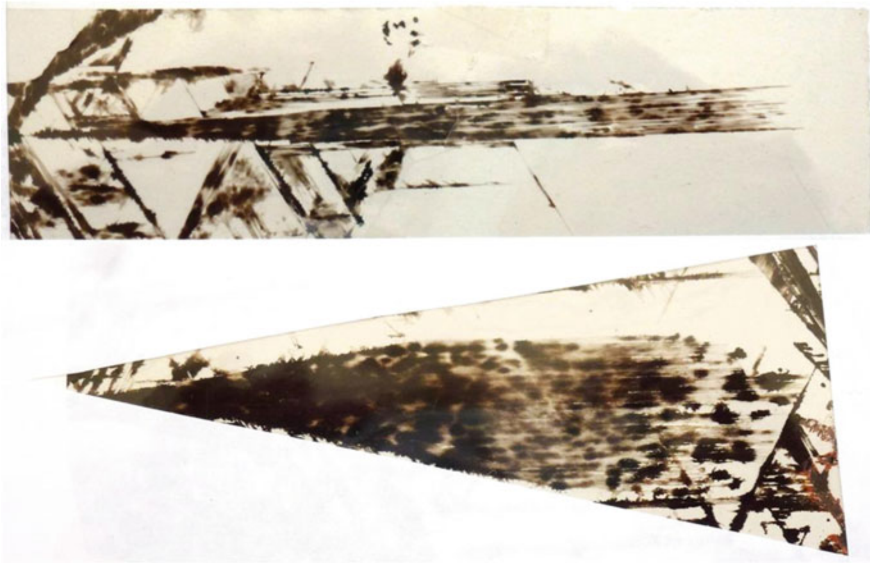

Fig. 1.12 Photographs of fans showing the internal structure of multiple parallel striae, which lie in the [010] direction or at 60 °C intervals to that direction in muscovite. They are 12 and 10 cm long, respectively

period of time by interacting with swift particles and those particles continue to interact as they recoil. Similar lateral spreading has been shown in hexagonal lattice arrays [4]. The marked instability of kink-pulses in the presence of thermal motion is well illustrated by the example of 100 eV impulses to an atom in the [110] direction in gold. At a temperature of 0 K in absence of zero-point motions the pulses propagated about 180 atoms before being extinguished but with zero-point motions included they failed to propagate beyond about 20 atoms along the chain (K. Nordlund, private communication, 2009). Hence, it is unlikely that the striae can be caused by individual kink-pulses of the type in which an atom in a chain is kicked towards the next atom in that chain. What is needed is a kink-like pulse that can propagate long distances along a chain and is *inherently stable against thermal motions and laterally stable*.

It has been shown that large amplitude motions of atoms in the [100] chain direction, using more realistic potentials for the mica structure, lead to an excitation that can propagate great distances in absence of any thermal motions [1]. This excitation is called a *crowdion* or *ultradiscrete kink* (UDK) to highlight the compactness of the excitation, since most of the energy involved is carried by only two atoms on a chain. The possible stability of a UDK against lateral spreading makes it a promising candidate for the excitation causing striae. It might be relevant to the existence of UDKs in mica that a MD study of adiabatic motions of potassium atoms in the mica

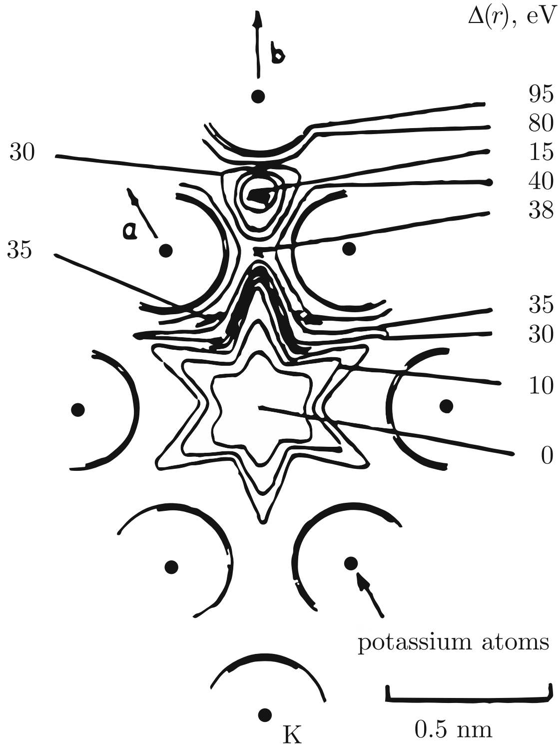

Fig. 1.13 Contour plot of the displacement energy for moving a potassium atom away from its equilibrium position, showing the location of a small secondary potential well. The displacements are assumed to be very fast or adiabatic so that the surrounding atoms have insufficient time to adjust their positions. Only one secondary well is shown in the [010] lattice direction, labelled b. Others occur in directions at 60° intervals. Reproduced with permission from [22]. Copyright © 1995, Elsevier

lattice showed the existence of secondary potential wells lying on chains in the [010] direction and at 60° intervals [22]. A contour plot of the energy of displacement is shown in Fig. 1.13; only one of the secondary wells is shown. In these directions the equilibrium separation of potassium atoms is 0.9 nm. Recent measurements by Russell on mica sheets have shown that the striae in fans lie parallel only to the [110] directions. A similar potential well is reported in the [100] chain direction [1]. It is possible that multiple UDKs moving in phase in line abreast provide some degree of collective lateral stability to those in the centre.

It is important to remember that muscovite crystals capable of recording the tracks of charged particles and mobile lattice excitations do not have the ideal lattice structure. They are under stress due to the relatively high, about 4 atomic %, content of iron that distorts the lattice. However, the amount of iron that is precipitated out to decorate the tracks, about 0.01 atomic %, is negligible relative to the total iron present. Hence, there is little change in the lattice associated with the recording process. It is remarkable that the various types of recorded tracks seem to be almost ubiquitous in mica despite the great variability of composition of natural crystals.

1.14 The Position at the Beginning of 2015

The position at the beginning of 2015 is considered in this section but new fundamental developments happened about February 2015 that are briefly described in the next section.

Iron-rich crystals of muscovite are still the only medium in which the paths of individual, nonlinear and uncharged, lattice excitations are visible. The astonishing sensitivity of the recording process invites the question as to what else might be recorded. There are several kinds of patterns decorated with magnetite that have not yet been satisfactorily explained.

The present state of the studies of lattice related transport phenomena is both interesting and challenging. This is because the recorded tracks in mica show that at least two kinds of nonlinear lattice excitations must exist. Recent improvements in modelling the muscovite lattice are revealing finer details of the behaviour of energetic atomic motions. However, the difficulty of modelling possible excitations in the presence of large amplitude thermal motion of the lattice atoms is still a limiting factor.

The nature of the atomic motions that allow the existence and remarkable stability of a quodon, especially at temperatures of up to 500 °C in real crystals, remains uncertain. In particular, there has been no experimental determination of their speed, which is expected to be subsonic. The best description in terms of known lattice excitations, which explains most of the properties of quodons, is given by the properties of mobile breathers. However, breathers are inconsistent with the observed properties of the excitations that delineate the fan-shaped patterns. The best description for the excitation causing the striae in fans seems to be an ultra-discrete kink or crowdion. These are expected to propagate at supersonic speed. It has recently been determined that the excitations causing the striae propagate only along chains parallel to [010] directions. This property and their decoupling from phonons needs to be confirmed if they are to successfully describe the tracks seen in fan-shaped patterns.

It will be interesting to see if ultra-discrete kinks or any other type of lattice excitation can exist and propagate useful distances in the diamond lattice structure of silicon. The observed behaviour of lattice excitation in the 2D layer of potassium atoms in mica is likely to be relevant to the growing interest in other 2D structures, such as those involving C, P, Si, Ge.

Finally, a better understanding of the recording process would assist in understanding the nature of the types of lattice excitations that yield recorded tracks in mica.

1.15 The Puzzle Solved: Quodons Have Charge

The final sentence in my review of tracks in mica said clearly that: a better understanding of the recording process would assist in understanding the nature of the types of lattice excitations that yield recorded tracks in mica. In February 2015 this comment proved to be prophetic. How that came to happen would make an interesting story for the future. Suffice it to say now that there were aspects of the recording process that were contradictory so were pushed to the back of one's mind. One such problem was why the amount of decoration on all the quodon tracks was the same but they were created with very different energies [2]. Then I looked at measurements made fifty years ago about the decoration on positron tracks. I saw that the extent of decoration on the quodon tracks was the same as that on positron tracks when the positrons were moving slowly at near sonic speed. A few moments later and I knew the answer to the question: What is a quodon? It is a nonlinear lattice excitation—most probably a breather—that has captured a positive or negative charge! The implications of this were astonishing and very exciting. It showed that a nonlinear lattice excitation could capture a hole or electron and carry it safely over millions of atoms at white hot heat in a layered crystal that was similar to all the high temperature superconductors. So I worked carefully through the consequences and how they might be tested. Despite being on holiday in Australia, within a month I was ready to present my results to experts at a Workshop held in Tartu.[1]

Acknowledgments I wish to express my thanks to Prof. Chris J. Eilbeck for his encouragement, financial support and most of all collaboration over many years. To Prof. Juan F.R. Archilla for his belief in me, constructive discussions and open mind. To Prof. Rob W. Witty for his foresight and essential financial support and to Dr. David R. Collins for applying his post-doctorate experience to the study of mica. Also, to Prof. J. Godfrey Fitton for providing chemical analysis of mica samples. I wish to thank Dr. Vladimir Dubinko for useful discussions about practical applications of the research. I am grateful to the University of Pretoria for providing me with an academic base.

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http://www.springer.com/978-3-319-21044-5

Quodons in Mica
Nonlinear Localized Travelling Excitations in Crystals
Archilla, J.F.R.; Jiménez, N.; Sánchez-Morcillo, V.J.;
Garcia-Raffi, L.M. (Eds.)
2015, XXV, 567 p. 272 illus., 183 illus. in color.,
Hardcover
ISBN: 978-3-319-21044-5