Transport Properties of Quodons in Muscovite and Prediction of Hyper-Conductivity

F. Michael Russell

Abstract The study of intrinsic localised modes in layered crystals has been advanced by the discovery that crystals of muscovite mica can naturally record small perturbations to the lattice after the crystal has grown but is still at high temperature. This led to the discovery of two types of nonlinear lattice excitations created by energetic atomic collisions that propagate great distances in flat sheets of atoms of potassium sandwiched between mirror silicate layers. One type, called a quodon, is stable and propagates along atomic chains without lateral spreading. The second type spreads laterally in the sheet about chain directions. It has recently been shown that quodons can trap and carry a positive charge at temperatures up to at least 500 °C. As the charge is transported in absence of an applied electric field it has infinite charge mobility. This leads to the prediction of lossless transmission of electricity at elevated temperatures, called hyper-conductivity. Here, studies are reported that show quodons can couple to holes and electrons. The strength of the coupling depends on the chemical composition of the crystals. Electrons are strongly coupled to quodons in calcium-rich crystals of muscovite, sometimes called brittle-mica. In crystals with negligible Ca only holes are bound strongly. This indicates that the transport properties of muscovite can be modified by local doping. Lastly, a third type of track recording process has been found in which a gas decorates the paths of energetic mobile lattice excitations. The most probable source of the gas is argon from the decay of ^{40}K.

Keywords Quodon · Muscovite mica · Charge mobility · Hyper-conductivity

---

F. M. Russell (✉)
Group of Nonlinear Physics, Department of Applied Physics I,
Universidad de Sevilla, ETSII, Avda Reina Mercedes s/n, 41012 Sevilla, Spain
e-mail: mikerussell@us.es

J. F. R. Archilla et al. (eds.), *Nonlinear Systems, Vol. 2*, Understanding
Complex Systems, https://doi.org/10.1007/978-3-319-72218-4_10

1 The Study of Lines in Crystals of Muscovite

The discovery in 1963 that black lines in natural crystals of muscovite held information relating to cosmic rays led to a study of the behaviour of nonlinear lattices when subject to energetic disturbances at atomic scales. After over fifty years, sometimes working alone but progressively with collaborators, the studies led to the prediction of infinite charge mobility in muscovite and to the possibility of transporting electricity without loss at any temperature up to 500 °C. The first definitive step in this protracted study began in 1967 with the finding of *Tracks in mica caused by electron showers* [8]. Since charged leptons left tracks it was expected that positrons emitted from the decay of the radioactive isotope ^{40}K of potassium in muscovite should also leave tracks. By 1985 this had been verified and led, by 1988, to unusual properties of *Positive charge transport in layered crystalline solids* [10]. This was followed in 1989 by the *Identification and selection criteria for charged lepton tracks in mica* [9]. The observation in 1993 of tracks in mica associated with nuclear recoils from ^{40}K decay, which were inconsistent with a relativistic particle origin, indicated the possible existence of stable, highly-localised, mobile nonlinear lattice excitations later to be called quodons [19]. In an attempt to explore what kinds of excitation might occur in a chain of nonlinear interacting particles in 1995 a mechanical analogue was constructed employing dipole-dipole interactions of magnets. It demonstrated the creation of a mobile, localised, discrete-particle oscillatory excitation that propagated for over 500 particle-magnets before being extinguished by air-friction. This analogue was the means by which the experimental study of the lines in muscovite crystals linked in to the extensive body of theoretical and numerical work on solitons, kinks and breathers or bions [4]. It also introduced a connection to experimental work done by a distant relative, namely Scott-Russell, on his '*Wave of translation*' [22]. The propagation of positive charge in a layered crystal, with possible relevance to the layered high T_c superconductors, prompted a study in 1996 of *Anharmonic excitations in high* T_c *materials* [17]. In 1997 the first of several extensive numerical studies of the properties of chains of discrete nonlinear interacting particles began with *Moving breathers in a chain of magnetic pendulums* [20]. The fact that the potassium atoms were held in place between tightly bound silicate layers suggested on-site potentials were important. Theoretical studies of possible intrinsic localised modes in anharmonic lattices in 1D and 2D arrays of discrete particles with on-site potentials pointed to quodons behaving like breathers. This led in 1998 to *Localised moving breathers in a 2D hexagonal lattice* [5]. This prompted further study in 2001 of *Breathers in cuprate-like superconductor lattices* [21]. The reality of these elusive excitations, the quodons, was demonstrated in 2007 by *Evidence for moving breathers in a layered crystal insulator at* 300 K [18]. Measurements on long tracks of quodons, some more than 20 cm in length, showed that they created secondary quodons when scattered by crystal dislocations. These secondary quodons always started with minimal track width but, while propagating, the width jumped to that typical of the parent quodon. The reason for this was unclear. To investigate if there was sufficient energy in the nuclear recoil of ^{40}K to create *A supersonic crowdion in* *mica* a study was made of the charge states in the decay of ^{40}K [1, 2]. This led by late 2015 to the realisation that quodons resulting from ^{40}K decay are always created in the presence of either a hole or an electron. This suggested that quodons might trap and carry either a hole or an electron. If it held a positive charge, or hole, then magnetite was precipitated on the track; if it was an electron then epidote was formed. However, for over 30 years there was an unexplained anomaly in the measured widths of the tracks of positrons as they slowed down. The early measurements had indicated that the width of a track progressively increased to a maximum but then rapidly decreased as the positron came to rest. The puzzle was why the track width should decrease as the positron came to rest, since it was the presence of a positive charge that triggered the recording process. This was resolved in 2015 when it was found that the end of the decoration on a track was not determined by motion of the charge but by the mechanical properties of the lattice. The precipitation of magnetite forming the decoration proceeded in the directions of lattice weakness. Since it had been found, by studying the tracks of positrons in mica, that the recording process precipitated magnetite in the presence of a positive charge, the similarity of widths of quodon and positron tracks provided, in early 2015, evidence for *Charge coupling to anharmonic lattice excitations in a layered crystal at* 800 K [13]. Exploring the consequences of this finding it was realised that the transport of charge by quodons in muscovite in absence of an applied electric potential across the crystal *indicated infinite charge mobility*, which led by April 2016 to the *Prediction of hyper-conductivity* at the Nolineal 2016 meeting. At that meeting a small group of participants decided to attempt to validate the prediction by an experiment. It is now clear that hyper-conductivity is fundamentally different from super-conductivity although both involve the unique properties of layered crystals. The background to the present work and a brief historical account is given in the book entitled **Quodons in Mica** [14, 15].

2 The Decoration on Tracks of Quodons and Charged Particles with Magnetite

The study of the properties of quodons and other non-linear lattice excitations in crystals of muscovite changed significantly during early 2015 when implications of the similarity of the extent of decoration on the tracks of quodons and slow moving positrons were re-examined [11]. The decoration with the black mineral magnetite takes the form of nanometre thick ribbons of variable width. Measurements on ^{40}K positron tracks show that the average rate of energy loss is less than 5×10^4 eV/cm or about one ionisation event per 10 micron of track length. Since the tracks are continuous the perturbation triggering the recording process must depend on electronic and not ionisation events, so is localised to less than 1 nm of the flight path. Measurements had shown that the width of positron tracks was proportional to the lattice perturbation and the decoration process magnifies this by a factor of about 10^4 thereby making the tracks visible. This lateral magnification of the initial lattice per-

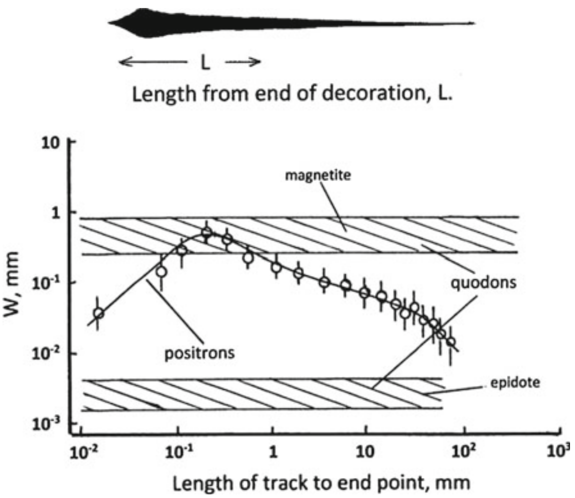


Fig. 1 Shape of typical positron track decorated with the mineral magnetite. Plot of the width of decorated tracks of positrons as they slow down compared with the average width of quodon tracks. This shows that recording process responds to quodons to the same degree as for nearly stopped positrons

turbation was found to be independent of the speed of the positrons in a given crystal. The amount of magnetite precipitated on the tracks varies from one crystal to another but the distribution along a track is, on average, the same. This is shown in Fig. 1. Was this similarity of track widths of slow moving positrons and quodons a property of the recording process or did it imply that a quodon perturbs the lattice to the same degree as a slow moving positron? When the idea of a quodon was first proposed, it was assumed that the excitation only involved relative motions of atoms within a small moving envelope [16]. Certainly, large amplitude oscillatory displacements of atoms within a quodon could create local changes in crystal potentials. Did the fact that in Fig. 1 the horizontal band of average width of decoration on quodon tracks intersected the measured width distribution curve of positrons have any significance? Might it imply that quodons could trap and carry a positive charge? If true, then it would be quite significant but there was a problem with this suggestion that hindered further study. It was known that the thickness of the ribbons of magnetite, normal to the (001)-plane, delineating tracks was approximately constant so the width of decoration should indicate the energy loss per unit length of track. The measured widths confirmed this relationship over most of the length of tracks of positrons except for the last part of less than about 0.5 mm from the supposed final rest position of a positron. The measurements indicated that in this region the extent of decoration decreased rapidly as a positron slowed to rest. This was at variance with the presumed cause of decoration, namely, the time during which a moving charge could influence a unit cell electronically to create a nucleation site. This dependence on dwell-time implied that the decoration should reach a maximum when a positron stopped and not while it was still moving. The resolution of this problem came from an unexpected direction involving chemical analyses of sheets of mica showing unusual patterns of decoration, which are now examined.

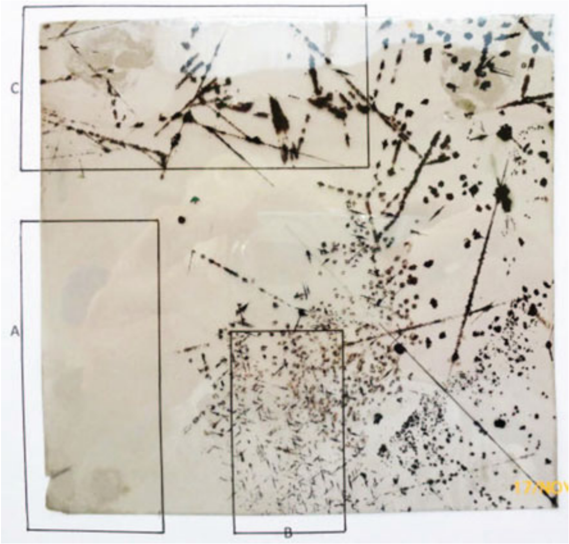


Fig. 2 Sheet used to study composition changes within a single sheet of 12 × 12 cm size and 0.5 mm thickness. The chemical analysis of the areas A, B and C is given in Table 1. The Fe content is high but there is surprisingly little variation of Fe between the different areas

In some crystals of muscovite the sensitivity of the recording process differs markedly in different regions of a sheet, as shown in Fig. 2. During the period when the recording process operates the hydrostatic pressure on a crystal should be isotropic and externally applied stresses applied to a crystal would not influence adjacent sheets inside a crystal differently. This variability of recording is unlikely to be due to a change of structure as the distribution of magnetite decoration was different in adjacent sheets cleaved from the same crystal, which showed no grain boundaries or fractures. The most probable local variable would be slight changes in the composition of a crystal. This was explored for the sheet shown in Fig. 2, which gave the results shown in Table 1.

The numbers in each column are the percentage by weight for the listed elements, the last column giving the sum-total. There are two main findings from this analysis. Firstly, all crystals showing magnetite decoration of tracks have a surprisingly high concentration of Fe. Secondly, there are only small differences in composition of the regions A, B and C. Might this point to catalytic involvement of a trace element in the recording process, such as sulphur plays in some photographic emulsions? The clear region A has lower Fe and Al and higher Si and K, these atoms being close to the K-sheets. Evidence for the reduced sensitivity of the recording process in B-type regions showing multiple ‘dot-like’ decorations was shown by the fading and eventual extinction of the decoration on tracks of quodons and muons as they entered such regions. When a positron is moving in the crystal the decoration follows the sequence of nucleation sites. However, when it comes to rest and annihilates it leaves a static permanent positive charge, which can trigger a lower sensitivity recording process. The ensuring accretion of magnetite strains the lattice locally so that the growth of decoration is determined by the mechanical properties of the crystal, proceeding in

Table 1 Table showing the chemical analysis of sections of a sheet showing different sensitivities for recording disturbances to the crystal. The most notable result of this analysis is that all the sheets showing decoration of tracks have about the same high concentration of Fe. The amount of Fe deposited in the decoration of tracks out of the total Fe content of muscovite ranges from less than 10^{-6} to about 10^{-4} for the most extensive decoration on fans. The regions of the first row-block correspond to the sample in Fig. 2. The last three row-blocks are for different crystals showing features of tracks decorated with magnetite. In sheets showing heavy decoration on fans, which are the tracks of laterally spreading kinks created in atomic cascades, there is significant substitution of Mg for Al (Table after Prof. J. G. Fitton from Edinburgh University)

	Sample name	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	TiO_2	MnO	LOI	$\sum$
Region B Stars & dots	Mica-01	44.89	31.73	6.45	0.85	0.10	10.353	0.275	0.077	5.00	99.73
	Mica-01	44.92	31.73	6.45	0.84	0.06	10.352	0.277	0.079	5.00	99.71
	Mica-01	44.98	31.68	6.45	0.85	0.09	10.356	0.275	0.078	5.00	99.76
Region C Quodons, etc.	Mica-02	45.54	31.16	6.44	0.93	0.08	10.489	0.269	0.075	4.89	99.88
	Mica-02	45.58	31.08	6.45	0.91	0.10	10.500	0.272	0.074	4.89	99.86
	Mica-02	45.56	31.13	6.45	0.91	0.10	10.491	0.273	0.075	4.89	99.88
Clear region Faint, good	Mica-03	45.92	31.18	6.20	0.86	0.04	10.620	0.257	0.072	4.43	99.59
	Mica-03	45.95	31.11	6.21	0.89	0.03	10.615	0.261	0.072	4.43	99.58
	Mica-03	45.95	31.13	6.20	0.89	0.06	10.616	0.264	0.073	4.43	99.62
Heavy fans	Mica-04	46.02	31.04	6.21	0.88	0.04	10.648	0.254	0.084	4.69	99.87
	Mica-04	46.04	31.02	6.21	0.89	0.02	10.658	0.257	0.082	4.69	99.87
	Mica-04	46.10	31.04	6.21	0.89	0.04	10.666	0.255	0.084	4.69	99.98
Good quodon tracks	Mica-05	46.26	29.89	6.39	1.53	n.d.	10.816	0.539	0.050	4.46	99.92
	Mica-05	46.24	29.92	6.39	1.49	n.d.	10.817	0.533	0.050	4.46	99.89
	Mica-05	46.26	29.88	6.39	1.51	n.d.	10.818	0.538	0.049	4.46	99.89
	Mica-06	45.97	30.73	6.28	1.26	n.d.	10.571	0.367	0.048	4.16	99.40
	Mica-06	45.93	30.68	6.30	1.29	n.d.	10.572	0.369	0.047	4.16	99.35
	Mica-06	46.00	30.74	6.29	1.28	n.d.	10.579	0.361	0.048	4.16	99.46

directions of lattice weakness. This is illustrated in Fig. 3. Deducting this part from the tracks showed that the rest position of a positron is at the maximum width of track. The corrected plot for the width of track of positrons as a function of distance from the stopping point is shown in Fig. 4.

This resolution of the decoration problem showed that the decoration caused by a quodon moving at near sonic speed matched that of an individual positron as it slowed to rest. Once it was realised that a quodon behaved as if it carried a positive charge it was then logical to consider how it might have trapped a charge. An analysis of the changes of charge states of potassium and daughter atoms in the several decay channels is shown in Table 2. In the dominant decay channel emitting electrons the recoil atom is positively charged. Only some of these decays will create a quodon because the component of momentum in a chain direction might be insufficient to form a quodon. In these cases, the energy is likely to be radiated as phonons leaving a stationary positive charge to trigger the magnetite recording process. This would account for the high volume-density of dots.

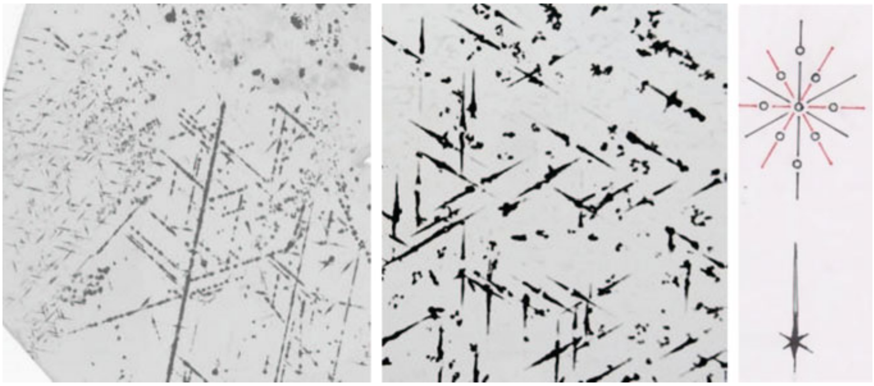
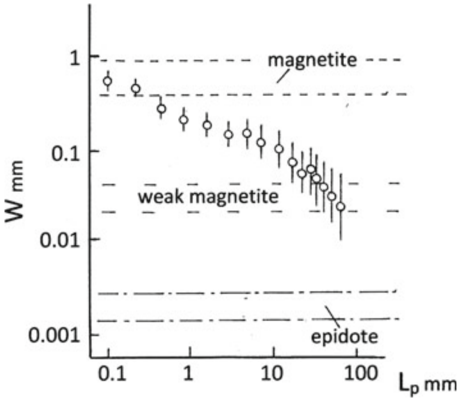


Fig. 3 The left hand side of the picture shows typical quodon tracks in the middle of the sheet, random damage spots at the upper right top and a region at the left containing many small dots of decoration; the sheet is 14 cm wide. The middle picture is an enlargement of an 8 mm wide part of the dot region. The right land side diagram shows a single dot and its relationship to the principal crystal directions. Quodons propagate in the red-line directions and the black-lines show the directions of lattice weakness. The dot region has reduced recording sensitivity but nucleation sites are provided by stationary positive charges. The two main sources of stationary positive charges are from the emission of an electron and rarely from annihilation of positrons. Precipitation on a single nucleation site proceeds in directions of lattice weakness, which are easily revealed in ‘percussion figures’ caused by striking a sheet with a dull point

Fig. 4 Plot of the width of decoration with magnetite on tracks of positrons and quodons after allowing for the decoration due to annihilation of the positron leaving a stationary positive charge. The decoration extends mainly in the directions of lattice weakness



Until the recording processes are better understood there will continue to be some unexplained effects. For example, in many of the dots in Fig. 2 the central region is apparently not decorated and appears as a clear area. These undecorated areas might indicate significant damage to the lattice that interferes with the decoration process, perhaps by the presence of an electron. The measured thickness of the epidote ribbons shows that they extend over at least two unit cells in the direction normal to the (001)-plane. This hints at possible pathways for Fe ions to migrate slowly between adjacent K-sheets. It is very likely that such migration occurs because of the concentration of

Table 2 Table of decay channels for ^{40}K. The last row in the second column in the table shows that the dominant decay channel leaves a single positive charge on the recoiling atom as it starts to create a quodon. Reprinted with permission from [1]. Copyright (2015) by Springer

Decay	Beta-	EC1	EC1+CE[a]	EC2[b]	Beta+
Intensity	89.25%	10.55%	0.001%	0.2%	0.001%
T (keV)	1311.07	1460	1460	1504.69	483.7
Emitted charged particle	e^-	None	Shell e^-	e^- (Auger)	e^+
Recoil from	$\nu + e^-$	Gamma	Shell e^-	ν	$\nu + e^+$
Max Recoil (eV)	42	29.2(M)	49.7(M)	31.1(M)	10
Daugther	Ca^{++}	Ar^+	Ar^{++}	Ar^{++}	Ar
Max V (km/s)	14.4	12(M)	15.7(M)	12.2(M)	7
Ionization of daughter (eV)	50.6	27.7	40.8	40.8	15.8
Δq (e)	+1	0	+1	+1	−1

[a] Subset of EC1 when the gamma is delivered to a shell electron
(M) Monochromatic
[b] Direct decay to Ar ground state, with recoil from 1504.69 keV neutrino emission;
3 keV Auger e^- emitted later
EC: electron capture; CE: conversion electron; T: energy available excluding rest masses
Ionization energy of K^+ 31.6 eV

magnetite on tracks in one sheet with adjacent sheets being devoid of any decorated tracks. Accretion of magnetite on tracks to create the final widths will be a slow process relative to the creation and initial decoration of nucleation sites. Table 2 also shows that the rare emission of a positron leaves a negative charge at the site of creation of a quodon. The track of a positron can be recorded by decoration with magnetite but the negative charge on a quodon, instead of decorating with magnetite, can cause the track to be decorated with the clear mineral epidote in crystals containing some calcium. In so-called ‘brittle micas’ there can be up to 1% of Ca in the K sheets. Using convergent beam electron diffraction techniques, it has been shown that, contrary to magnetite decoration, the epidote delineating the quodon track is not intrusive between the silicate layers [19]. Instead, it replaces the muscovite structure to give ribbons of epidote of 3.4 nm thickness, normal to the (001)-plane, that are geometrically compatible with the surrounding muscovite. Large crystals containing significant amounts of Ca occur much less frequently than those with little Ca, such as those showing strong staining with magnetite.

3 Absence of Identifiable Electron Tracks

Although quodon tracks decorated with magnetite are associated with electron emission from ^{40}K there is no evidence for electrons leaving their paths decorated with magnetite or epidote. Nor do they leave any identifiable track decorated with another mineral. There are several contributing reasons for this absence. Electrons do not show axial or planar channelling. When emitted they experience diffraction scattering but, in contrast to positrons, the angular distribution in the (001)-plane does not include peaks in chain directions. Instead, the probability for an electron propagating in a chain direction rapidly tends to zero. It is probable that the two recording processes are effective in proximity to the K-sheets because that is the plane of easiest cleavage. However, the progressive accretion of magnetite on the initial nucleation sites of quodon tracks arising from electron emission, leading to ribbon widths of order 1 mm, could conceal any short-range electron tracks emerging from the K-decay site. Despite these uncertainties the absence of evidence for tracks due to electrons in crystals of low Ca content suggests that they are less likely to be transported in the K-sheets than holes.

4 Migration of Argon from ^{40}K Decay

Surprisingly, a third decoration process has been found. Table 2 shows that about 10% of the decays of ^{40}K leave Argon. For many years this fact was ignored; being a noble element perhaps it migrated out of the crystals. When examining sheets of muscovite visually it often helps to observe them at near grazing angle against a white background. Sometimes the magnetite ribbons are close to a cleaved face and then appear brightly coloured because of interference of the reflected light. It was under such conditions that the sheet shown in Fig. 5 was observed. It shows regions where the lattice has been cleaved by a transparent intrusion, compatible with migration

Fig. 5 Pictures of the same sheet, the left by transmission and the right by reflection. The pictures show that there is distortion of the crystal structure both in the vicinity of magnetite ribbons and elsewhere where nucleation sites have been generated. The magnetite ribbons are built from unit cells of magnetite that are intrusive between the silicate layers. That leaves voids of small volume at the edges of the ribbons. At high temperature argon atoms could migrate to those voids. Later uplift to the Earth's surface would reduce the hydrostatic pressure causing distortion of the crystal structure

of argon. The intrusive magnetite decoration forces the silicate layers apart, thereby creating small volume voids at the edges of the magnetite ribbons. These would be suitable spaces for mobile argon atoms to accumulate. Later, the argon in these voids that is initially under high pressure would cause the silicate layers to be forced apart as the hydrostatic pressure on crystals is reduced by their uplift to the Earth's surface. This accounts for the visible distortion of the sheets near ribbons as seen by reflection, which is too large to be attributed to the distortion due only to the ribbons.

5 Creation of Secondary Quodons

A notable property of quodons with track widths indicative of a positive charge is their ability to create secondary quodons. The distance between successive secondary quodon tracks is random, consistent with scattering at dislocations. It is assumed that since quodons can propagate more than 10^9 atoms in a crystal at high temperature they are not scattered by point defects such as interstitials, atomic substitutions or vacancies. Usually, at a scattering event there is no change in width of their track, indicating that the charge is not lost. However, the secondary quodons usually are created with no charge, as evidenced by the minimal decoration of their tracks, as seen in Fig. 6. It is consistent with the trigger mechanism for precipitation of magnetite that the minimal decoration sections arise from local variation of the crystal potentials due to the large amplitude of atomic movements within a quodon. After travelling random distances from their point of creation a sudden increase in their track width indicates capture of a charge. This property of creating secondary quodons limits the type of excitation that constitutes a quodon. The large number, of up to about 100, secondary quodons generated by a primary quodon of maximum available energy of 42 eV points to a minimum energy for creation of a quodon of about 0.4 eV. Crowdions are a possible candidate for quodons but require about 27 eV for their creation. Assuming the nuclear recoil motion following decay of ^{40}K is in random directions then 2% (as calculated by the author) of the observed tracks could be due to crowdions. Lastly, the secondary excitations do not show the properties exhibited by kink-like excitations that create the fan-shaped patterns associated with atomic cascades [12]. The oscillatory nature of the internal motions of atoms in a quodon can transfer momentum to a secondary quodon in either the forward or backward direction. The secondary quodons are all connected to the primary track by weakly decorated tracks consistent with no trapped positive charge. The distance travelled before a charge is trapped is variable. Figure 6 shows secondary quodons arising from a primary quodon moving horizontally. This is consistent with the inability to subdivide the single charge on the primary quodon, so a secondary quodon is created neutral. It is interesting that a very small minority of quodon tracks lie in directions of chains with atomic spacing of 0.9 nm but the majority move in chain directions with 0.54 nm spacing.

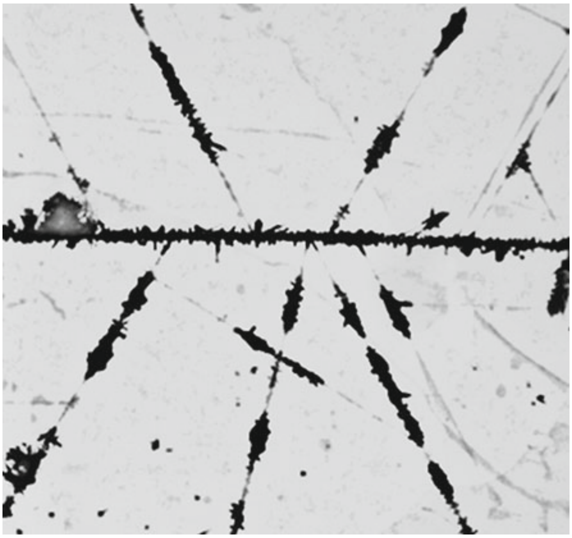


Fig. 6 Photograph of secondary quodons created by scattering of a primary quodon. The primary is moving horizontally. Since the charge on a quodon cannot be subdivided the secondary quodons are created without a charge but may trap one in flight

6 Re-examination of the Ejection Experiment

The experiment reported in 2007, designed to detect the ejection of atoms from a crystal by inelastic scattering of quodons at a crystal face, assumed that quodons were overall charge-neutral [18]. It is well known that atoms evaporated from a surface are usually neutral. However, the potassium sheets consist of cations and thus there was uncertainty about the ionisation state of ejected atoms so it was decided to introduce a region between the crystal and the detector to create a plasma through which ejected particles must travel to reach the detector. This would increase the probability for ionising ejected atoms that could then trigger the charge-sensitive channel- plate detector. The experimental arrangement is shown in diagrammatic form in Fig. 7.

A low activity source (1) of alpha particles from ^{241}Am irradiated one edge of a crystal of muscovite mica (3). This source and the crystal were held in a Faraday cage that is connected to the detector (4), also in a Faraday cage, via a voltage source. The purpose of the voltage source was to attract and focus positive ions to the detector and discriminate against electrons from field emission or other sources. Some positive ions from the low intensity plasma were detected and formed the background count-rate of the detector. It was also observed that UV radiation from an ionisation vacuum gauge contributed to the background count-rate. This effect was eliminated by introducing a multiple plate light-baffle between the gauge and the target chamber. The experiment looked for changes in the count-rate that could be attributed to effects arising from the alpha irradiation of the remote front edge of the crystal.

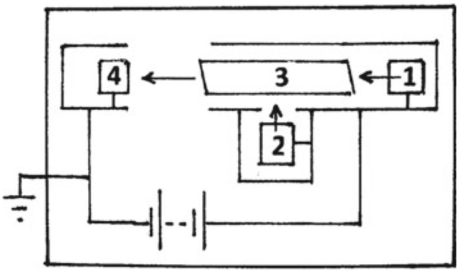


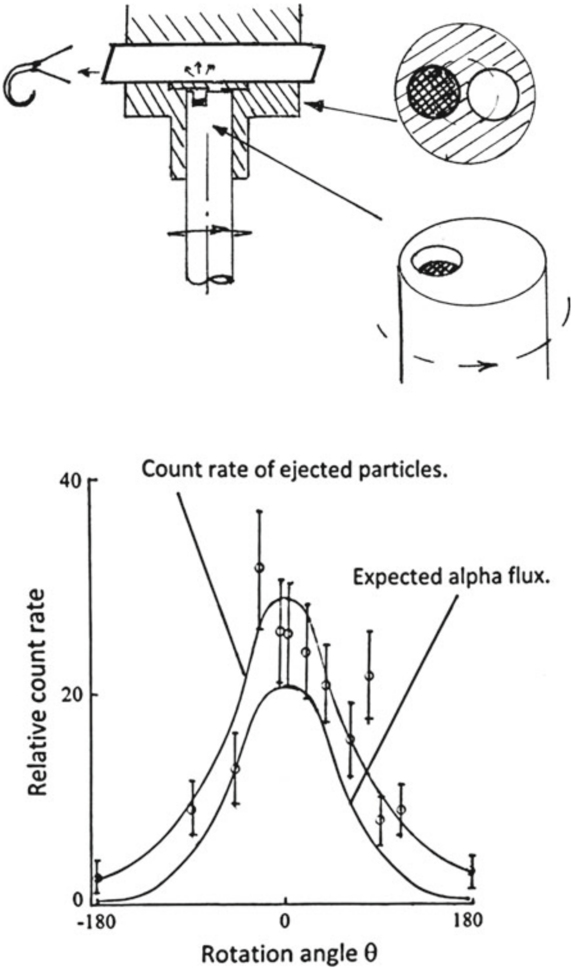
Fig. 7 Arrangement of the experiment for demonstrating ejection of ions from a remote crystal edge with the alpha source at position (1). To investigate the relationship between the alpha flux hitting the crystal and the detected count-rate the source was moved to position (2) where it could be rotated below a small hole in the metal plate supporting the crystal

By chance the supply of argon gas to the vacuum system to create a plasma ceased during a detection run. Fortunately, the vacuum pressure gauge readings were studiously recorded at the start and end of each run along with other parameters. The fact that the detector continued to record the arrival of charged atoms when the pressure was far too low to support a plasma went unnoticed. That is, the ejected particles must have had a positive charge when ejected. Only later, after the evidence from track-width data for quodons carrying charge was recognised, was the implication of the earlier experiment data appreciated. It showed that irradiation of one edge of a crystal caused ionised atoms to be ejected from a remote edge that was in a principal crystal direction from the irradiated edge.

Of course, there might be other ways for ions to leave a remote edge other than via quodon scattering. What was needed was evidence that the count-rate of ejected ions was proportional to the number of alphas irradiating the crystal with all other variables fixed. In particular, the geometry of the crystal holder, the detector and the alpha particle source had to remain unchanged. This would eliminate changes in the electric potential field distribution between the crystal edge and the detector. To this end the experiment was modified by moving the alpha source away from position (1) to position (2), still within the Faraday cage. The alpha source was mounted on the end of a metal rod that was inside a fixed metal tube, thereby causing no changes in geometry as the rod was rotated. The flux of alphas hitting the crystal then could be varied by rotating the rod holding the source under a hole in the metal support for the crystal. In this way, the flux could be varied from zero to a maximum value without changing any other parameter affecting the experiment. A sketch of the source arrangement and a plot of the measured count-rate as a function of the angle of rotation of the source is shown in Fig. 8 for one complete rotation.

There were three possible origins of charge on the ejected ions. One was the two positive charges of the alphas as they penetrated the crystal. The second source was the local ionization of the crystal by the alphas creating atomic cascades. The third source was the residual positive charge that was distributed through the crystal arising from the annihilation of the positrons from ^{40}K decay. The distance from the point of

Fig. 8 Drawing showing the construction of the enclosed alpha source that can be rotated within a Faraday cage to vary the flux of alphas irradiating the crystal. The plot shows the number of charged particles detected in regular 7 min intervals vrs the rotation angle and the expected variation from the geometry. The background count rate was 3 in the same time interval



entry to the crystal of the alphas to the crystal edge was about 3 mm. This exceeds by about three orders of magnitude the range of alphas in the crystal and of the zone of ionisation created by atomic cascades. The detection of charged particles leaving the crystal showed that charge must have moved through the crystal of muscovite. As muscovite is an excellent electrical insulator the charge must have been transported through the crystal by some kind of mobile anharmonic lattice excitation. The energy and momentum needed to eject particles from the crystal could only come from the scattering of the alphas in the crystal. This result, combined with the evidence from widths of tracks of positrons and quodons in muscovite crystals, points to the current being carried by quodons.

7 Long Range Transport of Charge at Elevated Temperatures

The great lengths of the tracks of quodons decorated with magnetite or epidote, typically exceeding 10 cm, showed the tight binding of holes and electrons, respectively, to the an-harmonic lattice excitations forming quodons. This is remarkable as the tracks are formed when the crystals are at temperatures exceeding 500 °C [3]. Moreover, the crystals are formed under natural conditions and thus contain many defects, such as interstitials, vacancies, atomic substitutions, radioactive decay products, ionisation from cosmic ray particles and dislocations. It is apparent that quodons are remarkably stable entities. Their recorded tracks show that they exist in the layered structure of muscovite, in crystals containing a high concentration of Fe and variable amounts of Ca. However, the crystals used in the ejection and charge transport experiments contained only modest amounts of Fe and no detectable Ca. Hence, the recording process was not functional. This suggests that it is mainly the layered structure that allows the existence of quodons. In each of the experiments there was evidence for the transport of charge through crystals of muscovite in the absence of an applied electric field across the crystal. This is indicative of infinite charge mobility at temperatures above ambient.

8 The Influence of Chemical Doping on the Recording Process

The first indication of useful information in the ‘staining’ seen in muscovite crystals were the long black lines that lay in random directions. Within the realm of known physics at that time, in 1963, muons were the most likely cause. Conclusive evidence for muons came only slowly. Measurements showed that they deviated slightly in a random way from straight paths, which was consistent with scattering. If they were the tracks of muons then they must be relativistic. With this assumption it was then possible to determine their energy spectrum. It was found to be similar to the known spectrum found from measurements made in underground particle detectors. Muons can be either negatively charged or positively for anti-muons. If positively charged then they should experience channelling in a crystal. When channelling was taken into account the corrected energy spectrum was consistent with the known spectrum. This was the first indication that the recording process precipitating magnetite responded to a moving positive charge. This was later confirmed by studying the decay products of ^{40}K. If the magnetite tracks were of electrons then the duration of the recording phase would be about 10^5 times shorter, because of the ratio of emitted electrons to positrons, indicating a recording period of order hours to days instead of hundreds of years. On the basis that geological processes are usually slow – except for earthquakes – the longer timescale was the more probable. This conclusion was later shown to be correct by observation of the unique diffraction scattering pattern of positrons in muscovite.

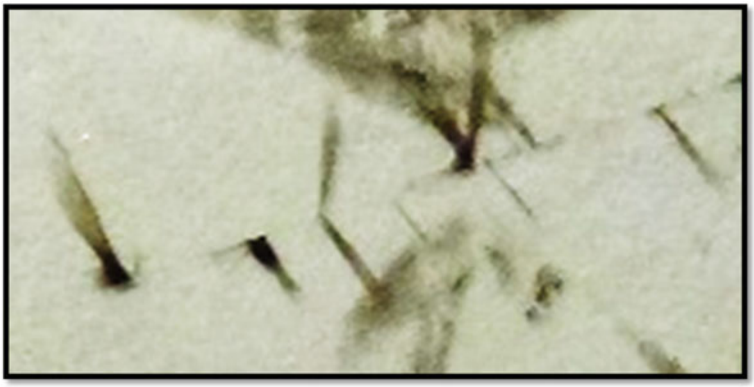


Fig. 9 Micrograph of muon tracks in muscovite showing fan-shaped decorations of lattice excitations created by nuclear scattering of the muons. These energetic scattering events create atomic cascades from which mobile nonlinear lattice excitations emerge. The quasi-2-dimensional structure of muscovite enhances the range of propagation of the excitations far beyond the range of typical discrete-particle shock-waves observed in molecular dynamic modelling studies of 3-D crystals. The portion of the sheet shown is 12 mm wide

There were three early indicators of possible stable lattice excitations capable of propagating great distances in muscovite crystals. In order of finding, firstly, in 1965, there were the fan-shaped patterns associated with nuclear scattering of muons. These are seen branching off from muon tracks in the micrograph shown in Fig. 9. Their range is typically 1 mm. Molecular dynamic studies of nuclear scattering events have given clear evidence for super-sonic discrete-particle shock waves in uniform crystals. An example is shown in Fig. 10.

Secondly, found in 1974, was the contiguous array of magnetite decorated tracks lying in atomic chain directions with a single track of a relativistic muon that is not in a chain direction. This is shown in Fig. 11. Either the muon intersected the contiguous array of unknown origin or, more probably, the array was created subsequent to a nuclear scattering of the muon dumping energy and momentum into the lattice.

The third indicator, in 1991, was the observation of clear tracks originating from the sites of ^{40}K decays that had emitted positrons in the opposite direction to the clear tracks. The material forming the clear tracks was identified as the mineral epidote [19]. This was the pivotal finding in defining a quodon because it identified a source of mobile lattice excitations that occurred throughout mica crystals. The physical properties of the source, the decay of ^{40}K, was well understood. It showed that the type of excitation that led to the fan-shaped patterns seen in Fig. 9 were fundamentally different from quodons. Although a supersonic discrete-kink like excitation describes some of the features of fans a detailed understanding of the excitation has yet to be achieved.

The quodons resulting from positron emission are created in the presence of a negative charge on the recoiling argon atom. A significant difference between tracks

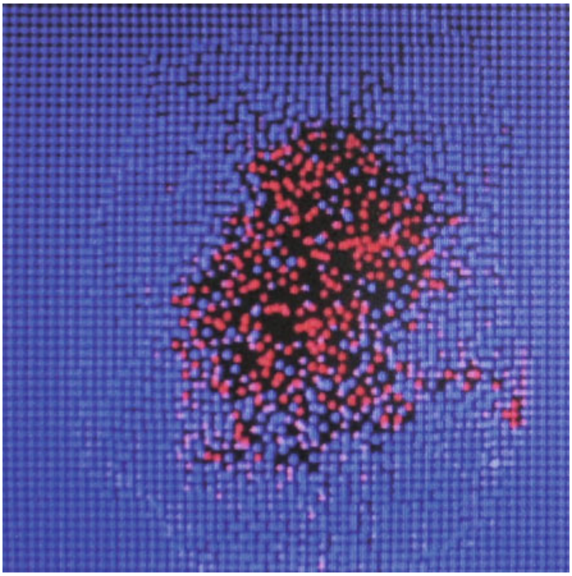


Fig. 10 Molecular dynamic study of a 5 keV impact to an atom in a crystal of gold. The figure shows a 2-atom thick slice through the atomic cascade, which stops obscuration of the shock-waves by the surrounding atoms in the crystal. The discrete-particle nature of the shock-waves, seen as irregular rings around the chaotic core, shows that only two adjacent atoms in a chain in the direction of energy propagation are involved in the lattice perturbation. These shock-waves are laterally dispersive in most uniform materials but in a quasi-2-dimensional layered crystal they are restricted in the direction normal to the layers. This enables the disturbance to propagate further in the layers, accounting in part for the large range of the fans. Reproduced from [6] after Ref. [7]. Licensed under CC BY-SA 3.0

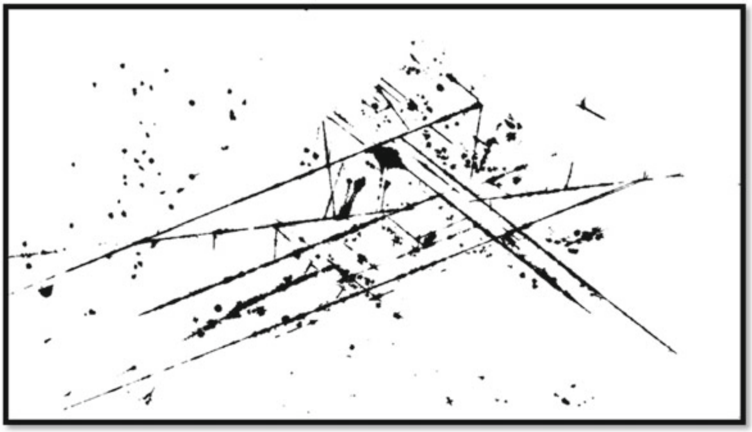


Fig. 11 This sheet shows the creation of multiple quodon tracks following a nuclear scattering event of a relativistic muon. The muon track lies at 8° to the horizontal and passes across the sheet. The sheet is 125 mm wide

decorated with epidote and those with magnetite is that the quodons creating epidote tracks appear unable to create secondary epidote tracks. Different epidote tracks can have different widths, which suggests that the width might be influenced by the quodon energy. However, each epidote track is of constant width. Although crystals with a high calcium content can show epidote tracks triggered by quodons and positron tracks decorated with magnetite they usually do not show quodon tracks decorated with magnetite. This suggests that in Ca-rich crystals holes are weakly bound to quodons. This might account for the absence of secondary quodon tracks decorated with magnetite arising from epidote tracks. In contrast to the creation of holes by annihilation of positrons, few free electrons are created near the K-sheets. This would reduce the probability for secondary quodons from epidote tracks capturing an electron and creating a secondary epidote track, as observed. It is unlikely that the epidote ribbons are dendritic growths in a meta-stable phase because of the apparent absence of secondary epitaxial ribbons in other crystal lattice directions. The lack of evidence for short sections of epidote tracks in magnetite decorated quodon tracks suggests that the ability of quodons to hold a negative charge is limited in crystals with low Ca content. A working hypothesis is that quodons are more tightly bound to holes than to electrons in crystals with low Ca content. Conversely, in Ca rich crystals electrons are bound more tightly than holes to quodons. The crystals used in the alpha irradiation experiments had low Ca content.

9 Polarisation and Residual Space Charge

The transport of charge by quodons in a layered crystal requires injection of sufficient energy and momentum to create quodons. This can be achieved by irradiating the surface of a cable containing suitable layered material with ions or neutral atoms. This method was used in the experiment in which ions, the alphas, were injected in the side of the crystal. Alternative methods might be found in the future. If ions are used, such as alpha particles, then charge is coupled to the material. This will cause a polarisation of the material. One result of this could lead to the build-up of voltage across the material. To estimate the possible significance of such an effect the arrangement and parameters of the ejection experiment is considered. The crystal was 7 mm wide, 1.5 mm thick and the dielectric constant of muscovite is about 8, giving a capacitance of about 1×10^{-13} F. The transport of one unit of charge by a quodon without loss by ejection causes a voltage difference of about 10^{-6} V. If 100 alphas per second impinge on the crystal and each alpha creates 10 quodons then the voltage across the crystal would increase at a rate of about 7 V/h. Each experimental run lasted about 24 h so a voltage of order 150 V might arise. However, this simple calculation assumes that no charge is removed or lost from the cable or crystal. In the ejection experiment charge was removed by the ejected particles.

In muscovite the decay of potassium leads to a distributed build-up of charge. The charge state of the daughter nucleus allows two routes: the dominant one yields a positive charge at the decay site and the minor one a positive charge by annihilation of emitted positrons. The rate is about 5 × 10^5 decays per day in 1 cc of muscovite. These positive charges occur in or near the potassium sheets. However, about 90% of these decays result in emitted energetic electrons. These eventually are distributed throughout the lattice as they are not concentrated in the potassium sheets by diffraction scattering. Although this causes nulling of the overall space charge it does not change the concentration distribution of holes in or near the potassium sheets, which are within reach of quodons. Consequently, about 90% of quodons are created with a positive charge and there is a good probability for secondary quodons, which are created without charge, to capture a positive charge in flight. Quodons resulting from external irradiation might be created with a charge. If the irradiation is with energetic particles capable of causing ionisation in atomic cascades then they could trap charges of either sign. As the majority of quodons are created in collisions in cascades with energies below that needed for ionisation they are most likely to trap a positive charge from any residual reservoir during their flight. This highlights the desirability of creating a reservoir of holes or electrons by doping of the layered material.

10 Evidence for Infinite Charge Mobility in Muscovite

These findings were presented at the Nolineal16 meeting held at Seville. June 7–10, 2016. The most important point came from the re-examination of the ejection experiments. It showed that charge could be carried through a crystal at near sonic speed by quodons in absence of an applied electric potential across the crystal. That was evidence for infinite charge mobility. In principle, it is a simple step to combine the know properties of quodons – ability to propagate great distances in imperfect crystals at high temperatures and transport of charge at near sonic speed – to the near loss-free transmission of electricity. In normal electrical conductors electrons and holes move or drift at relatively slow speed. This ranges from about a millimetre/sec in copper, several meters/sec in semiconductors, to a kmetre/sec in carbon nanotubes. In muscovite with quodons the speed is about 3.5 km/s at any temperature up to 500 °C. The only other know examples of infinite charge mobility are low and high temperature superconductors. It is to be expected that the observation of infinite charge mobility in the layered crystal muscovite will be of some interest in those studying high T_c superconductors (HTSC). To differentiate the apparent ability of quodons to transmit electricity at high temperatures and without loss in a perfect crystal from HTSC the term ‘hyper-conductivity’ was introduced. Certainly, there is an overlap with HTSC in that layered crystal structures are imperative in both cases. It led to a small group of people gathered round a white-board in the Group of Applied Physics at the University of Seville. They were discussing the possibility of verifying the evidence for infinite charge mobility in muscovite by an alternative procedure to counting individual ions by making a direct measurement of charge transported through a natural crystal. The safest way to design such a test was to build upon the earlier experiments using alpha particles to provide the energy and momentum needed for quodons and, additionally, a source of positive charges. The main unknown aspects in the design were the efficiency of creation of quodons and their efficiency of capture of a positive charge. This would determine the likely magnitude of any current that might pass through a crystal. The only way forward was to use the most sensitive current meter available at the University, which was a Keithley pico-amp meter. Although muscovite is a common mineral, and huge amounts are mined each year, small crystals of good habit are scarce. Several crystals were obtained by FMR from National Museums and by private purchase and one was sent to the Seville group.

Conclusion

The study of black lines and patterns in natural crystal of muscovite involved delving into multiple disciplines including cosmology, geology, nuclear physics, chemistry, solid-state physics, mathematics and numerical modelling. Sometimes the study had to await new developments in technology, especially in computing, and in assimilating new discoveries, such as channelling and intrinsic localised modes. There have been occasional tantalising diversions, like estimating the rate of fusion of hydrogen isotopes by quodons in a hypothetical layered matrix loaded with hydrogen. The main objective was to understand the origin of the lines and what they showed about anharmonic lattices and the excitations that could exist and propagate in layered crystals. It was the properties of layered structures that held the greatest interest because, in contrast to natural crystals, there is no limit to the composition and structure of sequentially deposited thin films or monatomic layers. With hindsight the strong coupling between electronic charge and anharmonic excitations should have been recognised earlier. Nevertheless, it led to evidence for infinite charge mobility and the prediction of hyper-conductivity in muscovite. In particular, it has set a critical test for verification of these phenomena. If a current is observed to flow in a crystal of muscovite, which has not been previously irradiated, by creation of quodons then the current should initially be large and then decay in time towards a finite limiting value. The source of the initial burst of current is the build-up and storage of charge from decay of ^{40}K. The asymptotic current stems from any charge introduced to the crystal in the creation of quodons that might involve ionisation of the crystal. If alpha particles are used then they will each contribute two positive charges.

Acknowledgements It is a pleasure to acknowledge the unstinting support, collaboration and guidance over many years given by J.C. Eilbeck who was able to link theory with experiment. More recently I wish to thank J.F.R. Archilla for his encouragement, collaboration and discussions on several aspects of the properties of muscovite. It is with both apprehension and anticipation that I await the result of his test of the prediction of infinite charge mobility. I also wish to acknowledge the University of Sevilla for nominating me as research collaborator in 2016. Part of this work was supported by a grant from Turbon Int. Ltd. Many people have assisted me at various stages and, in particular, I wish to acknowledge the support and guidance provided by R. Witty who enabled a critically important molecular dynamic study of the muscovite unit cell to be done by D.R. Collins.

References

1. Archilla, J.F.R., Kosevich, Yu.A., Jiménez, N., Sánchez-Morcillo, V.J., García-Raffi, L.M.: A supersonic crowdion in mica. In: Archilla, J.F.R., Jiménez, N., Sánchez-Morcillo, V.J., García-Raffi, L.M. (eds.) Quodons in Mica: Nonlinear Localized Travelling Excitations in Crystals. Springer Series in Materials Science, vol. 221, pp. 69–96 (2015)
2. Archilla, J.F.R., Russell, F.M.: On the charge of quodons. Lett. Mater. **6**, 3–8 (2016)
3. Deer, W.A., Howie, R.A., Zussman, J.: Rock-Forming Minerals: Micas, vol. 3A. The Geological Society, London (2003)
4. Eilbeck, J.C.: Numerical studies of solitons. In: A.R. Bishop, T. Schneider (eds.) Solitons and Condensed Matter Physics. Springer Series in Solid-State Sciences, vol. 8, pp. 28–43. Springer, Berlin (1978)
5. Marin, J.L., Eilbeck, J.C., Russell, F.M.: Localized moving breathers in a 2-D hexagonal lattice. Phys. Lett. A **248**, 225–232 (1998)
6. Nordlund, K.: A classical molecular dynamics computer simulation of a collision cascade (2008). http://en.wikipedia.org/wiki/File:10kevau_au.gif. Accessed 24 June 2017
7. Nordlund, K., Ghaly, M., Averback, R.S., Caturla, M., Diaz de la Rubia, T., Tarus, J.: Defect production in collision cascades in elemental semiconductors and FCC metals. Phys. Rev. B **57**(13), 7556–7570 (1998)
8. Russell, F.M.: Tracks in mica caused by electron showers. Nature **216**(5118), 907–909 (1967)
9. Russell, F.M.: Identification and selection criteria for charged lepton tracks in mica. Int. J. Radiat. Appl. Instrum. D **15**, 41–44 (1988)
10. Russell, F.M.: Positive charge transport in layered crystalline solids. Phys. Lett. A **130**, 489–491 (1988)
11. Russell, F.M.: Decorated track recording mechanisms in muscovite mica. Int. J. Radiat. Appl. Instrum. D **19**, 109–113 (1991)
12. Russell, F.M.: Energy gain by discrete particle non-linear lattice excitations. In: Carretero-González, R., Cuevas, J., Frantzeskakis, D., Karachalios, N., Kevrekidis, P.G., Palmero, F. (eds.) Localized Excitations in Nonlinear Complex Systems, pp. 289–315. Springer International Publishing, Cham (2014)
13. Russell, F.M.: Charge coupling to anharmonic lattice excitations in a layered crystal at 800 K (2015). arXiv:1503.03185 cond-mat
14. Russell, F.M.: I saw a crystal. In: Archilla, J.F.R., Jiménez, N., Sánchez-Morcillo, V.J., García-Raffi, L.M. (eds.) Quodons in Mica: Nonlinear Localized Travelling Excitations in Crystals. Springer Series in Materials Science, vol. 221, pp. 475–559 (2015)
15. Russell, F.M.: Tracks in mica, 50 years later. In: Archilla, J.F.R., Jiménez, N., Sánchez-Morcillo, V.J., García-Raffi, L.M. (eds.) Quodons in Mica: Nonlinear Localized Travelling Excitations in Crystals. Springer Series in Materials Science, vol. 221, pp. 3–33 (2015)
16. Russell, F.M., Collins, D.R.: Lattice-solitons in radiation damage. Nucl. Instrum. Methods Phys. Res. B **105**, 30–34 (1995)
17. Russell, F.M., Collins, D.R.: Anharmonic excitations in high T_C materials. Phys. Letts. A **216**, 197–202 (1996)
18. Russell, F.M., Eilbeck, J.C.: Evidence for moving breathers in a layered crystal insulator at 300 K. Europhys. Lett. **78**, 10004 (2007)
19. Russell, F.M., Steeds, J.W., Vine, W.J.: Formation of epidote fossil positron tracks in mica. Optik **92**(4), 149–154 (1993)
20. Russell, F.M., Zolotaryuk, Y., Eilbeck, J.C., Dauxois, T.: Moving breathers in a chain of magnetic pendulums. Phys. Rev. B **55**, 6304–6308 (1997)
21. Russell, F.M., Marin, J.L., Eilbeck, J.C.: Breathers in cuprate superconductor lattices. Phys. Lett. A **281**, 21–25 (2001)
22. Russell, J.S.: Report on waves. In: Report of the 14th meeting of the British Association for the Advancement of Science, pp. 311–390. John Murray (1845)