DISCRETE AND CONTINUOUS
DYNAMICAL SYSTEMS SERIES S
Volume 4, Number 5, October 2011

doi:10.3934/dcdss.2011.4.1267
pp. 1267-1285

PERSISTENT MOBILE LATTICE EXCITATIONS IN A CRYSTALLINE INSULATOR

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Abstract. We examine tracks in crystals of muscovite of high energy charged particles, and of mobile lattice excitations created by kinetic atomic scattering. The mobile lattice excitations are interpreted as a type of breather, here called a quodon. The typical energy of a quodon can be found from the decay of potassium K^{40} atoms in the crystal and supports their interpretation as a type of breather. In turn, this establishes a unique signature for energetic quodons, the 'kinked-line' tracks, allowing discrimination against tracks formed by charged particles. The stability of quodons against crystal defects and thermal motion is considered. Measurements on energetic quodon tracks, with flight paths up to 530mm, show that they can propagate more than 10^9 unit cells with no evidence of energy loss. This suggests that quodons might persist indefinitely in certain crystals of high quality. Evidence is presented for a new type of mobile lattice excitation that is capable of creating energetic quodons, which also is stable against lattice defects. Possible practical applications of quodons are considered briefly. Although quodons can induce fusion in deuterium or tritium present indications are that the rate is too low to be of practical use. Finally, a nonlinear lattice effect that might increase this rate is suggested.

1. **Introduction.** Nonlinear transport phenomena in solids are of increasing practical importance as techniques for their study and use are developed. In this connection natural crystals of the mineral muscovite mica are important because they can reveal nonlinear transient perturbations of the lattice at the atomic scale. Figure 1 is a photograph of a typical sheet that is easily cleaved off the layered crystal and is shown about half life-size. The dark lines are entirely natural in origin and do not need any special treatment or development. Some of these lines have been identified as the fossil tracks of charged subatomic particles [17]. However most of the lines, although superficially resembling the tracks of charged particles, are inconsistent with that origin. Studies of these lines led to the hypothesis that they were the tracks of quasi-particles consisting of highly localised, uncharged, mobile excitations of the lattice. Because of their association with quasi-one-dimensional atomic structures in the crystal they were called quodons [18, 19]. Subsequent studies showed that they are consistent with interpretation as a type of Intrinsic Localised Mode or breather [11]. Here, the term quodon is used to signify a mobile, longitudinal optical-mode (LOM) breather with energy in the range from a few eV upwards to perhaps hundreds.

Although breathers can, in principle, be either stationary or mobile, it is self-evident that quodon tracks are created by mobile quasi-particles. Early evidence for the origin and identity of quodons came from their close association with tracks

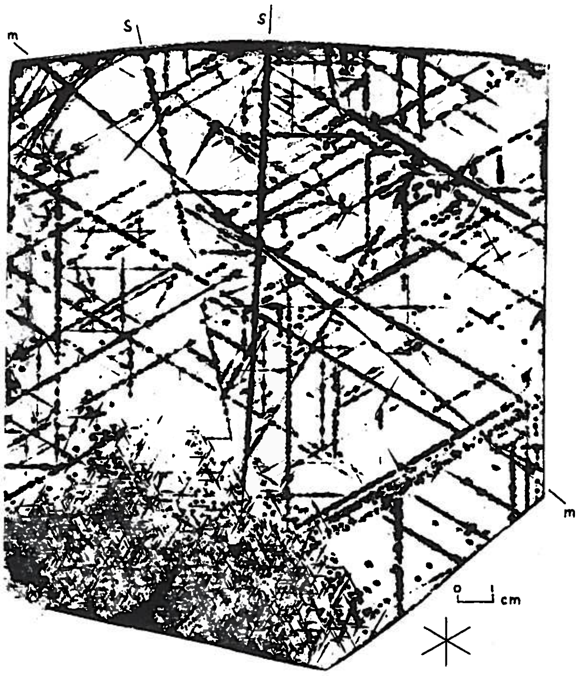

FIGURE 1. Scan of sheet of mica showing many tracks of energetic lattice excitations called quodons. These lie exactly in atomic chain directions as indicated by the line diagram. Also shown is the track of a cosmic ray muon (m-m) and two tracks from a nuclear star (s,s). Note the scale bar of 1 cm.

of high energy muons within nearly perfect crystals. It is well known that muons suffer multiple-scattering in passing through a solid and such events would couple both energy and momentum to the scattered atoms and thus to the lattice. Initially, how such a scattering event caused a stable, uncharged, mobile quasi-particle was unknown, but results pointed to some kind of nonlinear lattice excitation like, for example, a Toda soliton. Unfortunately, it was known that Toda solitons are unstable in two, and by inference three, dimensional arrays [14]. However, an obvious difference is that atoms in mica are subjected to on-site potentials that define their equilibrium positions, whereas these are absent in the Toda case. Inclusion of this on-site term led to breathers and quodons. That an impulse to an atom in a crystal evolves quickly into a stable, highly localised, lattice excitation that is mobile is interesting but the remarkable feature is the stability of the ensuing quodon. This aspect is examined further below, and suggests possible practical applications. Since some of the important properties of quodons have been found from studies of their tracks in mica, it is relevant to examine the structure of muscovite and the principles underlying the recording process, especially as some recorded events still are not understood.

2. **Recording process.** During growth of these crystals deep underground and at high temperature, various impurities, principally of iron but also manganese and calcium, can be incorporated into the structure. These appear either in solid solution as interstitials or as substituted atoms. During subsequent slow cooling these impurities reach a state of saturation. Further cooling leads to the non-equilibrium state of super-saturation when small perturbations of the lattice can initiate precipitation of the impurity to create nucleation sites. This is achieved by temporarily lowering the potential energy barrier inhibiting spontaneous precipitation. As expected, lowering of the barrier is charge sensitive, a positive charge assisting precipitation whereas a negative charge inhibits the process. A local positive charge could result from ionization or passage of a positively charged particle through the crystal. It can also result from large amplitude oscillations of atoms about their equilibrium positions in the lattice, which causes local potentials of alternating sign. In this case, once an impurity atom has been assisted over the barrier, the subsequent reversal of the local potential raises the barrier and so holds the impurity atom in its new place. As there is no evidence that quodons are charged, this is the probable route for recording their tracks. The nucleation sites are subsequently decorated by accretion of impurity, thus rendering the initial transient lattice perturbations permanent, and eventually visible to the unaided eye. This decoration of the tracks by growth of crystal-orientated dendrites occurs after the position of the track has been defined uniquely by the moving particle or quasi-particle [3]. Precipitation also can occur at significant lattice defects such as fractures, but there is no clear evidence for it at dislocations. This might be because they do not lower the inhibiting barrier, or perhaps there is a scavenging of impurity for the decoration process. Except for ionization losses, the energy needed to form the permanent tracks is derived from the exothermic phase change involved in the precipitation, and so comes from energy stored in the lattice and not from the moving particle or quodon. Depending on the chemical composition of the crystals, which can tolerate moderate variations from the generic structure and a large range of concentrations of impurities, the precipitation leads to formation of magnetite Fe_3O_4 or epidote $Ca_2(Al_3Fe_3^+)(SiO_44)(OH)$ [25]. Magnetite is an opaque electrical conductor and delineates most of the lines in mica, whereas epidote is a transparent insulator that can be observed by phase-contrast methods in some crystals with high Ca content. Muscovite is an excellent insulator and is transparent, which allows these tracks and features to be studied.

The discovery that some of the lines in mica were fossil tracks of charged particles showed that the recording process operated at the atomic level and was remarkably sensitive. For swift charged particles causing ionization, the sensitivity of the recording process is such that the creation of ionization sites, each requiring only a few eV of energy, about every 10,000 atoms along a flight path is sufficient to leave a permanent continuous track. The process for recording the passage of a positive charge in between ionization sites is even more sensitive in that the particle apparently loses no energy. An example of such a track is shown in Figure 2. Once the impurity has been precipitated it is not possible to replicate the non-equilibrium conditions for this process by reheating the crystal. Even now the fossil tracks in muscovite continue to be of interest, as they are the only known way to study the creation, propagation and behaviour of individual quodons in an insulator, as well as other transient disturbances to the lattice such as radiation damage caused by swift ions.

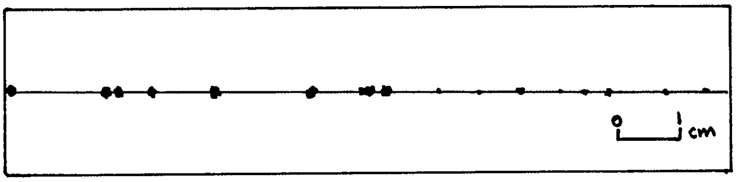

FIGURE 2. Scan of track of high energy charged particle showing decorated ionization sites and continuous recording of track in absence of ionization. Note scale bar of 1 cm.

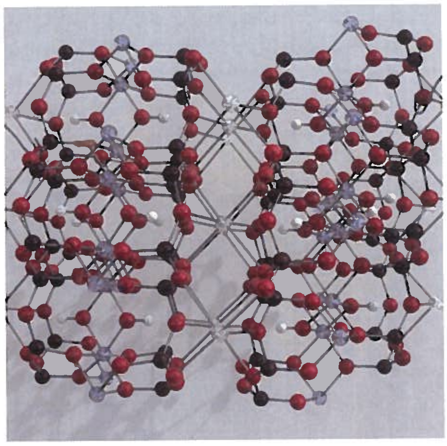

FIGURE 3. Photo of structure of muscovite mica. The potassium atoms (clear) lie in the middle plane sandwiched between identical sheets of silica tetrahedral (silicon-red, oxygen-brown). The potassium atoms bond with aluminium (white) by Van der Waals binding. The open nature of the lattice holding the potassium sheet is seen clearly. This open nature and also relatively open channels connecting adjacent potassium sheets allow impurity atoms to diffuse easily through the crystal.

The generic formula for muscovite is $K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$. It grows as crystals with a layered structure that can be split easily to give thin transparent sheets. This easy cleavage arises from the weak bonding of single sheets of potassium atoms sandwiched between complex silicate-based layers [5]. The structure is illustrated in Figure 3. The minimum spacing between the potassium atoms is large at 0.53nm, which reduces the rate of energy loss by ionization of charged particles moving in the vicinity of the potassium sheets relative to the bulk material as, for example, when planar channelling. Potassium has three isotopes K^{39}, K^{40}, K^{41} with relative abundances 93.4, 0.01, 6.6, respectively. The K^{40} isotope is radioactive with three decay channels, but only two emit particles, either electrons or positrons in the ratio

$10^5 : 1$, respectively, of approximately the same maximum energy. In 1cc of muscovite there are $\sim 2 \times 10^4$ K^{40} decays per second. Clearly, only a small fraction of these produce tracks that are recorded permanently. The charge sensitivity of both the recording process and the ability to channel discriminates against electrons in favour of positrons, but responds equally to the stationary positive charges created during ionization by either of them. Next, there is selection due to the solid angle for flight in the recording layer. Also, the short tracks of electrons will be masked by decoration of the localised ionization and the effects of the recoiling nucleus, which are the prime cause of the quodon tacks.

3. **Detection and creation of quodons.** The observation of tracks of positrons from K^{40} decay - identified by their large range and ability to channel, unique Rutherford scattering distribution, increase in rate of energy loss as they slow down and diffraction scattering by the lattice - showed that the recording process operated in the vicinity of the potassium sheets. Hence, quodons must propagate in the potassium sheets for their tracks to be recorded. Their tracks occur only in directions parallel to certain crystallographic directions which correspond to straight chains of atoms. Since one end of a quodon track was often coincident and coplanar with a charged particle track, it showed that there was a causal relationship between them and pointed to kinetic scattering as the link. These facts suggested that quodons were closely associated with the dynamic behaviour of chains of atoms. Molecular dynamic studies of the muscovite structure showed that only in specific chain directions in the sheets of potassium atoms was the force resulting from displacement of one atom towards another collinear with the displacement [5]. To a first approximation, in these directions the atoms surrounding the chains are arranged such that atoms of the same element are arranged in pairs either side of the chain and equidistant from it, thus satisfying C_2 symmetry, although this is not obeyed exactly in muscovite. The angles these pairs make with the chain direction seem not to be critical. These results suggested that the properties of such chains and sheets could be studied by means of magneto-mechanical analogues consisting of a sequence of interacting particles arranged in a straight line. In the early analogues gravity-pendulums were used to give a linear on-site restoring force, with nonlinear magnet dipole-dipole interaction between particles. In later analogues the nonlinear magnet dipole-dipole interaction also replaced the linear gravity term. Little difference in behaviour of quodons was seen in these two cases. In later numerical modelling studies the particles interacted through Lennard-Jones potentials. These two methods allowed the dynamic behaviour of chains and 2-dimensional arrays to be examined in detail and over long periods of time relative to the natural period of oscillation of adjacent atoms [11, 22, 12].

After the quodon hypothesis was proposed in 1994, circumstantial evidence for them accumulated, especially in connection with radiation damage. Indeed, their existence seemed almost inevitable, yet more than ten years after that proposal, they remained hypothetical. This was partly due to there being no known way to detect individual quodons in flight and partly because the conditions needed for recording their tracks can not be replicated in the laboratory. However, studies with the analogues suggested a way forward. It was observed that if the first magnet in a chain was hit sufficiently hard then the resulting quodon, when it reached the end of the chain, could eject the last magnet from the chain. This process is illustrated in Figure 4a and was the basis for a laboratory experiment. In the experiment, quodons

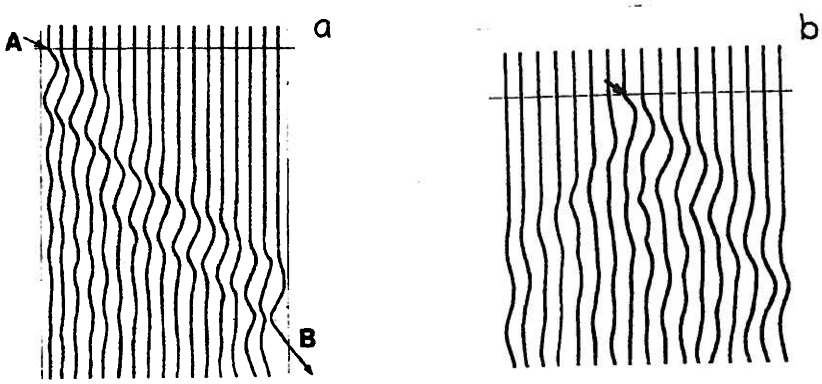

FIGURE 4. Plots of the displacements of atoms about their equilibrium positions for a series of equally-spaced atoms in a chain as a function of time, obtained with a magnet-analogue of an atomic chain. Fig 4a: shows how an impulse to the first atom in the chain evolves into a quodon that moves at sub-sonic speed towards the end of the chain. At the end of the chain it is inelastically scattered and ejects the last atom. Fig 4b: shows how two quodons are formed if the impulse is applied to an atom in the middle of a chain. The direction of the impulse determines the strongest quodon.

were generated by bombarding one edge of a mica crystal with alpha particles from a radioactive source. The quodons then propagated through the crystal along chains until they reached the opposite edge of the crystal. There they would be reflected unless the kinetic energy and phase of the atoms within a quodon was sufficient to eject the last atom in the chain. The experiment confirmed the predicted effect and showed that ejection could occur after the quodons had travelled more than 10^7 atoms along chains [21] Since the experiment was conducted at about 300K, it also showed that quodons are not coupled to the thermal phonon background, as such coupling would cause them to lose energy to the lattice.

There are now other possible ways to study quodons based on their inelastic scattering at lattice discontinuities. One is to use transmission electron microscopy (TEM) to explore the effect of quodons on moving and annealing radiation damage defects. Another way is to make use of their ability to transport kinetic energy through a crystal insulator, without loss of energy and independent of any temperature gradient, and dump that energy at a boundary where the resulting small change in temperature could be detected. Detection could be by means of the rapid transition from superconducting to normal states near the critical temperature Tc in some materials.

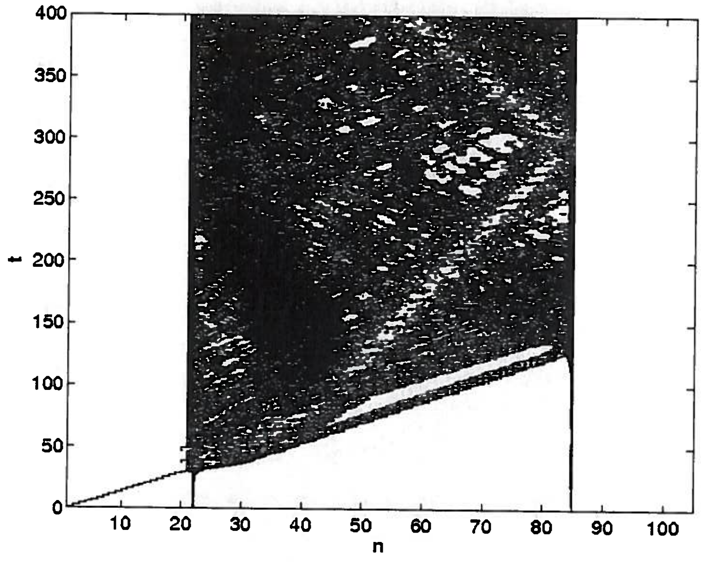

FIGURE 5. Numerical simulation of an atomic chain, showing the creation of a quodon that is reflected from the end of the chain. It shows how the energy of the impulse that is not taken by the quodon is radiated away.

The efficiency of creation of quodons created by inelastic scattering of swift particles either inside a crystal or its surface has been examined via analogues and numerical modelling. The efficiency, defined as the ratio of the total kinetic energy contained within the envelope of a quodon to the energy given to the impacted atom, depends on several factors. If the struck atom is within a crystal then some energy is coupled to the adjacent proceeding atom in the chain in the opposite direction to the motion of the quodon, by rebound of the struck atom. This embedded case is illustrated in Figure 4b. In this case the efficiency is about 60%. On the other hand, if the struck atom is first in the chain and is not ejected backwards following the first recoil motion, then the efficiency is about 80%. These efficiencies relate to quodons of intermediate energy, comparable to the energy needed to eject an atom from a surface, that is, of order 10eV. Numerical studies show that the remaining energy propagates away from the scattering event in a complex manner, probably consisting of a mixture of low energy quodons, breathers and phonons. Figure 5 is one such example, showing a quodon forming from an impact and later reflected from a boundary, together with faster moving but low energy excitations of the lattice.

Measurements indicate that quodons become less stable against scattering by small crystal defects as their energy decreases. Evidence for this comes from tracks of secondary quodons created by scattering of more energetic quodons at lattice defects. It was found that the average distance travelled by a quodon before creating a secondary quodon tends to decrease as the energy decreases. It is assumed that the volume density of crystal defects is approximately constant in a given crystal. The fact that this process does not lead to a tree-like end to a quodon track is

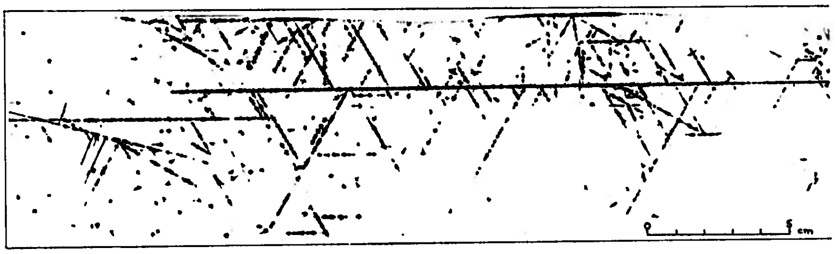

FIGURE 6. Scan of a long quodon track showing creation of multiple secondary quodons. Some secondary quodons scatter to produce tertiary quodons. Summing over all tracks indicates the energy of the primary quodon was > 100eV. Note scale bar.

probably due to lower energy quodons being unable to initiate the recording process. An example of such a sequence is shown in Figure 6. The primary quodon is unlikely to have total energy exceeding ~300eV, because molecular dynamic studies of the muscovite structure indicate that atoms with greater energy could become interstitial. There are five secondary quodon tracks of average length 40mm and each of these lead to about three tertiary tracks of ~10mm length. In turn, each of these lead to about five tracks of ~2mm length. Below this length it is not possible to distinguish quodon tracks from dendrites associated with the decoration process. Overall, the visible portion of the primary quodon track gave rise to more than 100 daughter tracks, which indicates a minimum energy for a quodon capable of leaving a track of ~3eV. It is expected that eventually quodons in non-perfect crystal insulators will degrade into phonons.

For many years there have been reports of 'anomalous transmission' effects in studies of swift particles moving in crystals. Of special interest was the observation of atoms ejected from the rear face of a crystalline gold foil in TEM studies. The probability for electrons scattering off the last atom at the surface is very low relative to that for scattering in the bulk material. This suggests that there exists some mechanism that allows transport of energy and momentum through the crystal to eject the last atom as a result of scattering of an electron within the crystal. In this connection the decay of K^{40} in mica allows the dynamics of quodon creation to be studied in some detail, but for positrons instead of electrons. This decay has a unique signature which allows clear identification.

Since K^{40} atoms lie at lattice sites, the angular distribution of emitted positrons is determined by diffraction scattering, leading to sharp peaks in chain directions. Axial channelling will lengthen their flight path, aiding in their identification. The emission is a three-body event: positron, neutrino and recoil nucleus. Hence, for positrons of highest kinetic energy of 1.5MeV, corresponding to longest flight paths, the neutrino has minimal energy and the recoil nucleus is directed essentially in the opposite direction to the positron. Examination of the longer positron tracks from K^{40}, that lay in chain directions in calcium-rich but iron-poor muscovite, showed that frequently there was a long thin line of uniform width, composed of epidote, that extended from the point where the magnetite decorated ionization track of the positron started. Since epidote can not occur naturally in muscovite, the phase change necessary for its occurrence must have been triggered by some perturbation to the crystal, with quodons created by nuclear recoils the only known and expected cause. TEM studies show that the ionization track and the epidote line are coplanar. For positrons of lower energy than the maximum the recoil nucleus will not move in a chain direction, but the impulse to the lattice will have a component in the nearest chain direction, usually the same as that of the positron. Despite the fact that epidote cannot occur naturally in muscovite, the possibility that the epidote part is simply a spontaneous growth initiated by a magnetite-to-muscovite discontinuity can be ruled out, because no such lines are found starting from a point somewhere along the positron flight path. Typically, these epidote lines can have lengths exceeding 70mm, with widths of about 1 micron. The maximum length of positron tracks in this category with an epidote tail was 53mm. For a positron of maximum energy of 1.5MeV, the energy of the recoil nucleus is 49eV. Allowing for the efficiency of generation of quodons with embedded atoms, this gives a quodon energy of ~40eV. At the opposite end of the positron energy spectrum, where the neutrino has maximum energy, the quodon created in a decay will have the same energy as for positrons of maximum energy, but there will be no associated magnetite-decorated positron track. These bare epidote tracks are observed, but cannot be differentiated from quodon tracks derived from the electron decay channel. This method cannot be used to investigate the production of quodon tracks decorated with magnetite in iron-rich muscovite, as there is no clear way to identify the decay site. Nevertheless, nuclear recoil is the most probable cause of the majority of quodon tracks, with K^{40} decay the main source, followed by high energy particles derived from cosmic rays, then by alpha decay of uranium and lastly by spontaneous fission. Both of the lepton decay channels of K^{40} will cause ionization locally, and are the most likely cause of the large number of decorated events seen in some crystals, but positive identification is prevented by the masking effect of the decoration. This is seen in the lower left hand part of Figure 1. The reason for the great variation in the number of decorated events per unit volume is not known, but is probably due to variations in composition of the mica and the rate of cooling, as these regions usually occur at the edge of crystals.

In most scattering events, the momentum vector of the impacted particle will not be directed exactly in a chain direction. Early studies of atomic collisions using hard-sphere approximations of atoms showed that in off-axis impacts, there was focussing of the momentum vector in a chain direction, as the amplitude of lateral oscillations decreased [24]. However, this focussing action was shown to be impaired by thermal motion. Similar focussing was observed in nonlinear 2-dimensional magnet analogues, and in numerical models of 2-dimensional arrays. The studies using analogues also showed that, although transverse optical-mode (TOM) excitations could be created in chains, only the LOM excitations, the quodons, were able to cause ejection of particles from a chain. Moreover, the excitations with highest energy were always of LOM type. The creation of quodons, by in-line nuclear recoil examined above, is consistent with them having LOM internal motions.

4. **Variable parameters and selectivity of recording process.** The impurity content of muscovite crystals is quite variable, and selection is necessary to find sheets that are suitable for detailed study of specific aspects of the tracks. The iron content can vary by several orders of magnitude, but this does allow the consequences of different concentrations of impurity to be examined. If the iron content

is very low, <0.001 Fe ions per unit cell, then the recording process cannot operate. As the iron content increases, the sensitivity of the recording process increases, but the rate of energy loss by ionization of channelled charged particle also increases, thereby reducing their range. When the iron content is sufficiently high to record quodon tracks, >0.01, the range of positrons from K^{40} is too short for their clear identification. As the iron content increases further towards 0.3, the decoration of the tracks also increases, and can become sufficiently massive as to preclude measurements.

Another variable is the rate of cooling of a crystal as it passes through the track recording stage. This will affect the sensitivity of the recording process. Slow cooling reduces the sensitivity, which discriminates against recording quodon tracks, but leaves the sensitivity for ionization-based tracks unchanged. This is because ionization persists in an insulator. Slow cooling also gives delicate decoration of tracks, enabling accurate measurements to be made on them. The iron content will also influence the onset of recording, as the crystal must cool further at low iron content to reach the saturation point. Fortunately, the impurity content can vary as a crystal grows, so that the effect of different concentrations within a crystal can be examined, as the rate of cooling will be the same throughout the crystal. In addition to these variables, the amount of impurity available to record new events will decrease as existing tracks are progressively decorated. Another factor is the temporary local depletion of available impurity to record a disturbance of the lattice.

As a result of these variables some crystals show only the tracks of charged particles, whereas others can be dominated by events arising from lattice disturbances such as quodons. Finally, crystals frequently show depletion of impurity in the vicinity of their edges, which probably is due to leaching. As a consequence crystals smaller than ~50mm across a face seldom contain lines. Although these many variables cause problems, they can be managed with experience.

5. **Signature for quodon tracks and their stability.** It is difficult to distinguish between the tracks of quodons and those of high energy charged particles that lie in chain directions due to channelling. Fortunately, the process of focussing energy into chains allows a unique signature for some quodon tracks. Consider a charged particle of positive sign that is travelling in a direction that intersects the recording plane of a sheet of potassium atoms. Since it is not moving in a recording layer, it will not leave a permanent track. If it is scattered by a potassium atom, the path of the particle could be changed to lie in the recording layer. The impulse on this scattered atom will have resolved components in both the plane of the recording layer and the normal to that plane. Since in muscovite there are no chains of atoms in directions that intersect the plane of potassium sheets, then out-of-plane quodons can not be created. However, the resolved impulse in the potassium sheet could create a quodon that will propagate in the chain direction that lies closest to the track of the particle in the recording layer, but in the opposite direction. Later, the reverse process might occur with the particle scattering out of the recording layer. This later scattering will create another quodon, that propagates in the chain direction closest to the particle track before it is scattered. The scattered particle, again, will leave no permanent track. This sequence of events gives rise to a unique signature for quodon tracks as illustrated in Figure 7. It consists of two parallel tracks that are separated by, but joined to, a track that lies in a non-chain direction. Such 'kinked-line' configurations are easy to identify. The most likely candidate for

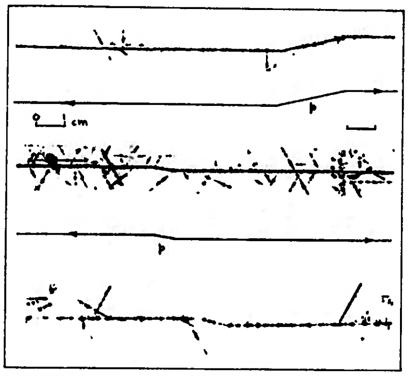

FIGURE 7. Scan of three examples of 'kinked-track'. These are produced by a proton scattering in to the (001)-plane of potassium atoms and later scattering out from the plane, producing a quodon at each scattering. Note scale bar.

the charged particle responsible for a kinked-line configuration is a proton as it is known that protons with energies in the MeV region are part of the underground cosmic ray background.

The laboratory demonstration of ejection of atoms by quodons showed that they can propagate more than 10^7 unit cells in a natural crystal, with little loss of energy. Good quality muscovite crystals, as used in that experiment, typically contain $\sim$ 0.001 ions of Fe per unit cell in the vicinity of the potassium sheets, presumably in the space between the potassium atoms. Hence, each quodon would have interacted with about 10^4 impurity atoms during its flight, yet still had sufficient energy to cause ejection. To explore the range of quodons a search was made, principally in museums, for large sheets of muscovite mica that showed delicate decoration of particle and quodon tracks, which were identified by the kinked-line configuration. To date the longest track found of an individual quodon is 530mm, equivalent to $\sim 10^9$ unit cells. It seems that the range is limited only by the size of crystal available. Since the widths of decorated quodon tracks decrease as they loose energy it should be possible to estimate the rate of loss of energy along the tracks. However, measurements on long tracks not showing secondary quodon production show no change in average width within the errors of measurement set by the variability of the decoration process. For tracks of length >200mm this gives a reduction in width of less than 5%. This indicates that quodons can propagate $> 10^{10}$ unit cells in natural crystals having a moderate iron content. As there are no known crystal defects that occur only at these scales of distance, there is no reason to think they cannot persist indefinitely in real crystals containing the usual types of defects.

To study the persistence of quodons, extremely long flight paths in nearly perfect crystals would be needed, which clearly is impossible using natural crystals. In principle, an effectively infinite crystal might be achieved by constructing a thin crystalline film on the surface of a cylinder. It is known that quodons can negotiate curved or bent layers without loss of stability because their tracks can cross over decorated tracks in nearby layers, the decoration causing local distortion of the layers. However, there is an alternative way to study their stability involving total

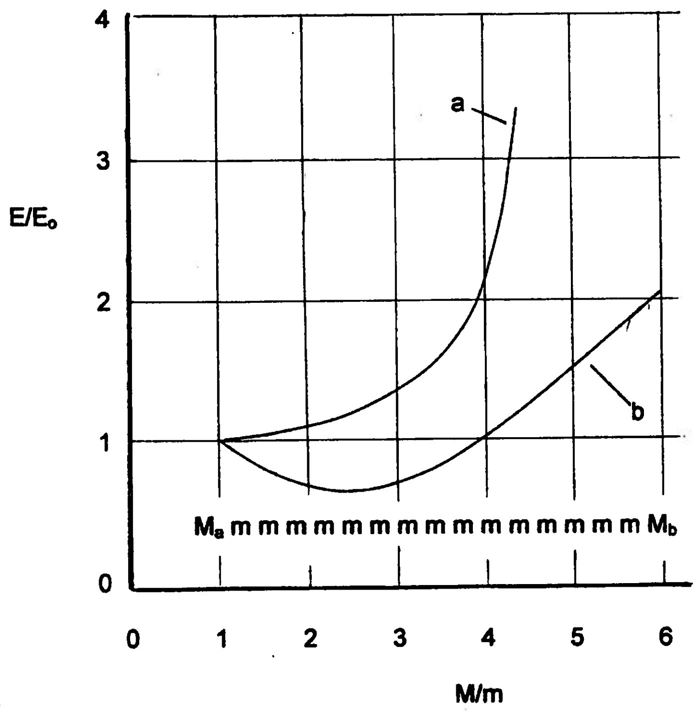

FIGURE 8. Graph showing how increasing the mass of the last atom in a chain (a) or the first atom (b) changes the energy needed of the impulse to cause ejection of the last atom. Results obtained with magnet-analogue.

internal reflection at a surface or boundary. This can be achieved by increasing the mass of the last atom in a chain. The increase in energy of a quodon needed to cause ejection as the mass of the last magnet in an analogue was increased is shown in Figure 8 curve (a) for constant strength of the end potential energy barrier. This suggests that quodons could be totally reflected at opposite ends of a crystal by depositing a thin film of a heavy element. Increasing the mass of the first particle in the chain initially assists the creation of quodons, as shown in curve (b). In this way it might be possible for quodons to be trapped within a crystal, but that raises the question of how to detect them.

6. **Coordinated creation of quodons.** The high sensitivity of the recording process in muscovite means that other types of transient lattice excitations probably have been recorded. We now consider instances of events giving rise to multiple

quodon creation. Since the cosmic neutrino energy spectrum extends up to extremely high energies, occasional instances of high energy baryons underground are to be expected. In most cases these will have positive charge, either inherent or by stripping off outer electrons. If they leave a recorded track, then they must have been moving near the potassium layer. Such tracks should be identifiable as they are expected to show enhanced or extensive decoration due to their high rate of energy loss by ionization. Despite their low rate of creation underground, typically $\sim$100 per m^3 of muscovite crystal compared to $\sim 10^5$ muons, a few examples have been found. As they pass through matter, they will be scattered. In addition to producing atomic cascades and quodons, the nonlinear nature of these scattering events means that collective processes such as solitons, kinks and shock-waves are likely. These nonlinear excitations of the lattice might, in principle, lead to the creation of multiple quodons. Following a high energy scattering event the struck atom will initiate a forward-directed cascade that spreads laterally, the crystal structure influencing its development in space. In this initial stage the displaced atoms can have supersonic speeds as the front of the cascade expands. Near the start of a cascade, the crystal structure is disrupted and, together with some ionisation, can be recorded but due of their small size they will be masked by the decoration. Cascades are energetic events, and so should be the source of nonlinear lattice effects. In Figure 9 the track of a heavily ionizing particle is shown near full size, from which several wedge-shaped patterns or 'fans' emerge. Cascades are the most probable cause of these fans. Within the fans there appear to be multiple quodon tracks that stem from the sides of the fans, as illustrated in Figure 9. One interesting but as yet unexplained feature of these fans is that the sides do not lie in chain directions but are confined within the directions of chains closest to those of the quodons. It is apparent that the moving disturbances causing the sides contains sufficient energy to create multiple quodons. That is, they are precursors of quodons. Of course, once a quodon is created its energy is removed from the nonlinear disturbance expanding from the cascade.

7. **Applications of quodons.** In view of the generic nature of Intrinsic Localised Modes such as quodons and breathers, it would be surprising if they are not involved in various processes, although that involvement might not yet be recognised. For example, the high temperature superconductors have layered structures in which breathers can exist but it is not known why superconductivity involves layered structures [20, 13]. However, there is growing interest in this topic [16]. At present there are three aspects of quodons of potential practical significance. The first relates to modification of materials by exploiting the high effective temperature within a quodon envelope, defined in terms of atoms having the same kinetic energy. There is already evidence for this effect, in connection with phase-transitions in non-equilibrium systems [2]. The decorated lines in mica are another example. A second field for expected application is in the annealing of crystal defects, again due to the high effective temperature of atoms in a quodon [23, 1, 7]. The shrinkage of radiation-induced voids in materials is a persuasive example of quodon annealing [8]. For quodons with energies in the range 1 to 40eV the equivalent temperature range is 7.5×10^3K to 3×10^5K, respectively. It has been suggested that atomic chains play a role in the annihilation of defects in small radiation dose annealing of semiconductors [4, 6]. With annihilation energies in the range 3 to 10eV, this would be compatible with creation of quodons. The possibility of releasing energy stored in

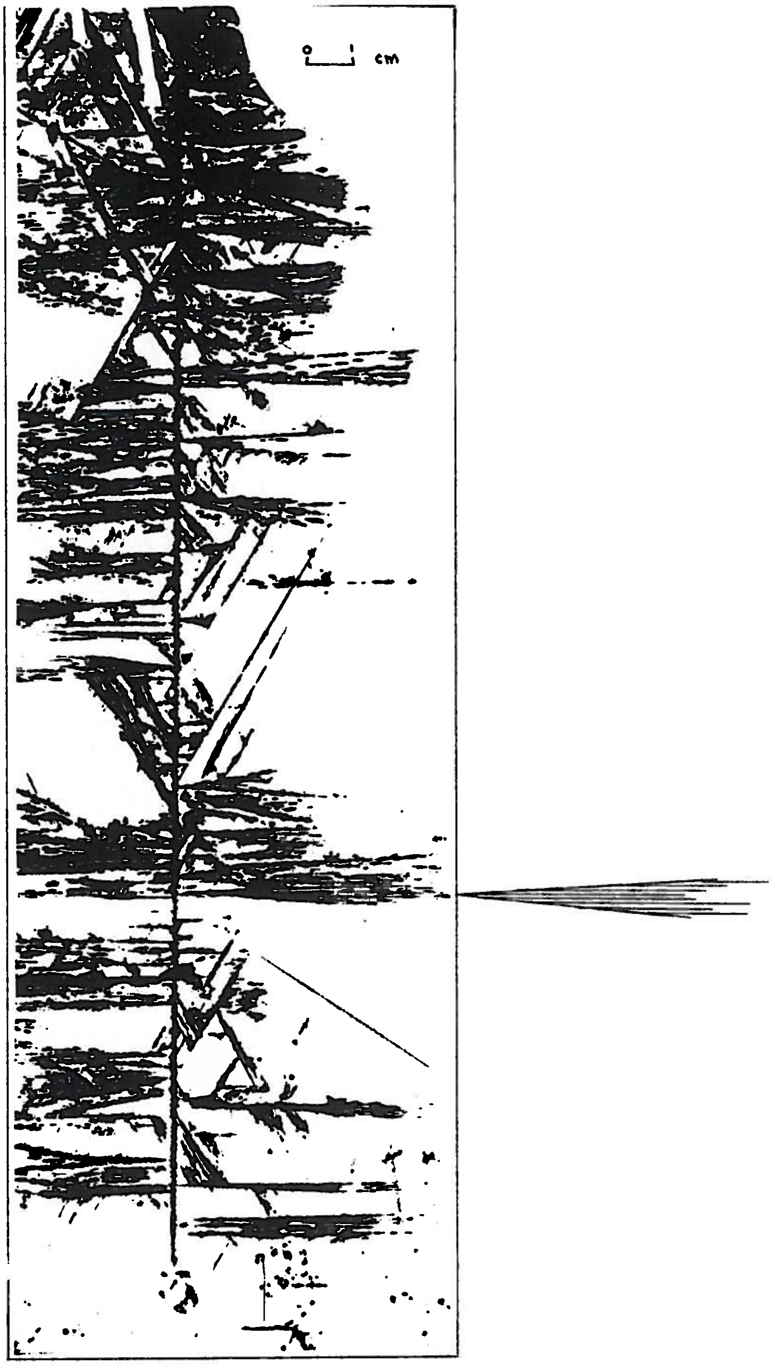

FIGURE 9. Scan of track of charged particle producing multiple 'fan', which give rise to multiple quodons. The diagram indicates multiple quodon production. Note scale bar.

a chain at local potential wells has been examined briefly using an analogue model. The result is shown in Figure 10: a small disturbance Fig 10b to the first atom in the chain does not release the stored energy, but a larger one Fig 10c initiates a sequential release. The initial disturbance could be by a quodon.

The third potential application is the transport of kinetic energy through a solid, in absence of a temperature gradient, and seemingly without loss of energy in transmission. The kinetic energy of swift particles, perhaps from a nuclear reactor, is coupled to the lattice via quodons, and at a remote point is converted to thermal energy in an absorber. Suppose each quodon is isolated within a volume 1000 times the volume of its envelope. The number per unit volume is then 3×10^{18} cm-3, which move at a sub-sonic speed of ~1000m/s. If the energy per quodon was only 10eV then the rate of energy transfer would be of order 3.10^{25}eV/s. or $4\mathrm{MW/cm}^{-2}$.

There is an additional highly speculative possible application area that relates to the long-term stability of quodons and the nature of atomic motions within their envelopes. Once a quodon is created then atoms of high speed are repeatedly brought close together in head-on collisions without expenditure of energy. This process is not impeded by thermal motions of the atoms. If this happened in a crystal containing deuterium, then there would be an enhanced finite probability for fusion to occur, no matter how small the fusion cross-section might be. As this process depends upon the surrounding lattice to contain the high speed atoms it has been called Lattice Assisted Nuclear Fusion, or LANF [9]. It is well known that the fusion of light nuclei at low energies involves quantum tunnelling to penetrate the Coulomb barrier. This is the process underlying all known routes to controlled fusion. The cross-section for fusion varies exponentially with the kinetic energy of the colliding nuclei, becoming extremely small for low energies; for energies down to 300eV in DD see [15]. But, crucially, there is no lower cut-off: if a quodon persists indefinitely then eventually a fusion event will occur. It is estimated that it takes about 10^{22} collisions to fuse two hydrogen nuclei in the Sun. The principles underlying LANF are consistent with known physics and will cause fusions. Although it seems that the rate of fusion is too low for it to be a viable source of power when using only quodons, it is useful to examine this idea to see how the rate of fusion might be increased within the LANF concept by invoking other nonlinear effects.

8. **Quodon based LANF.** There are three basic requirements for LANF to be viable. Firstly, quodons must exist and be stable in a crystalline fuel containing hydrogen isotopes. Secondly, they must have high enough energies to cause usefully high rates of fusion. Thirdly, there must exist a fuel that retains its structure at a temperature high enough for generation of useful power. For present purposes, lithium deuteride, LiD, is a possible fuel. It is a crystalline insulator with melting point of 962K. It has a cubic structure and so consists of alternating layers of lithium and deuterium atoms in the (111) planes. Moreover, it complies with the structural conditions identified above for the existence of quodons propagating in those layers. It is an insulator with low thermal conductivity at 400K of about $\sim 5\mathrm{Wm}^{-1}\mathrm{K}^{-1}$. However, quodons would provide an excellent route for removal of kinetic energy released by fusion and its release external to the fuel. LiD is not radioactive.

The relatively high melting temperature of LiD suggests the maximum energy in a quodon E_q would be of similar order to that in muscovite, the upper limit set by the displacement energy ~300eV. However, it is expected that there would be interactions between quodons propagating in opposite directions leading to a

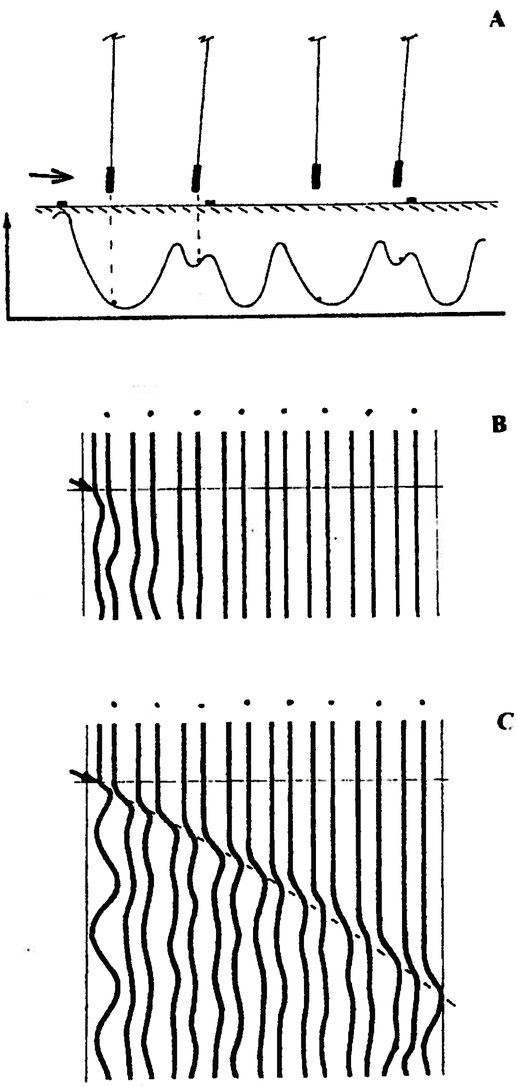

FIGURE 10. Plots of the displacements of atoms as a function of time, obtained with a magnet-analogue of an atomic chain. Alternate atoms have extra stored energy. Fig 10b: the impulse is too weak to trigger the release of the stored energy. Fig 10c: the impulse is sufficient to release the stored energy.

increased maximum energy of individual atoms. This is similar to the important Maxwell's tail in plasma reactors. Also, the containment provided by the lattice could minimise atomic displacements. This sets a maximum for the equivalent temperature of atoms in head-on collisions in interacting quodons, defined in terms of kinetic energy by $2E_q/3k_b$, of $\sim 4.10^6$K. Further, since the fuel is a solid, the colliding nuclei experience full electronic shielding. Here, no allowance is made for possible effects due to electron screening in a solid or the possibility of resonant tunnelling [10].

It is instructive to follow the flow of energy released in a fusion event. Each D, D fusion releases ~3MeV and as it occurs in a solid fuel the products n, He^3 or p, H^3 will cause cascades in the fuel. Initially, the energy per particle in a cascade will be high so they have a relatively high probability for inducing another fusion. Next, nonlinear precursors of quodons might be formed. As these precursors and the cascades continue to develop the kinetic energy of the atoms involved progressively falls until at about 300eV displacements are no longer possible. It is at this stage that quodons are formed, up to $\sim 10^4$ per fusion. As the swift particles are moving in three dimensions, only two thirds will form quodons in the (111) planes, and only half of these will be moving in the preferred direction in both the Li and D chains. Hence, about 10^3 quodons will begin their flight in the D chains, continuing until they are either degraded by scattering at a major crystal defect, or initiate a fusion. During their flight through the fuel they might anneal lattice defects produced in the cascades. If only one of these quodons succeeds in causing a fusion, then the process is self-sustaining, ignoring the possibility of extra fusions by particles of higher energy in the early stages of the cascades.

In the following example, all parameters are pushed to their limits to get an estimate of the fusion rate. The probability for fusion is $\sigma(E_q)N$ where N is the number of head-on collisions per unit area and $\sigma(E_q)$ is the cross-section for fusion per collision at energy E_q. The number of collisions is given by $N = W_2 fm$ where W_2 is the number of chains supporting quodons per unit area, f is the frequency of oscillation of atoms in a quodon and m is the number of oscillating atoms in a quodon with near maximum energy. The rate of fusion is then $\sigma(E_q)NLv$, where L is the number of quodons per unit length of crystal and v is their speed of propagation. Hence, under equilibrium conditions, the fusion power density is $\sigma(E_q)NL$. Assume that chains with quodons are surrounded by 10 chains without them to give good isolation, then $W_2 \sim 2.5 \times 10^{14}\text{cm}^{-2}$; suppose quodons are separated along a chain at 2nm spacing so that $L \sim 2.5 \times 10^6\text{cm}^{-1}$, assume $f \sim 10^{14}\text{sec}^{-1}$ and $m \sim 5$. If the E_q is ~300eV then $\sigma(E_q)$ is about 2.10^{-23}cm^{-2}, giving a power density of $\sim 4\text{Wcm}^{-3}$ or ~4MW per cubic metre. However, if E_q is ~150eV, then the power density drops to about 50mW per cubic metre. Of course, substituting tritium for deuterium would increase the rates by a factor of ~300, but this would introduce major problems. Moreover, if the volume density of quodons did approach the limit suggested here, then the energy stored in the quodons would be considerable. If it were averaged out over all the atoms in the crystal then for E_q ~300eV the average energy per atom would be about 7eV, which is comparable to the energy of formation of LiD, namely, 6.2eV. This might lead to instabilities in the crystal structure. Hence, it is concluded that the contribution of quodons to additional fusions is negligible. Indeed, their principle role might well be in annealing radiation damage. However, the exponential increase in cross-section with energy of the colliding atoms suggests that it would be logical to look at the nonlinear high energy stages in the development of cascades that lead to the creation of quodons. The obvious place to start would be the poorly understood 'fans' since they involve a large number of atoms as the disturbance propagates into the crystal.

Acknowledgments. The support given by Turbon International Limited is acknowledged.

REFERENCES

[1] G. Abrasonis, W. Moller and X. X. Ma, *Anomalous ion accelerated bulk diffusion of interstitial nitrogen*, Phys Rev Lett, **96** (2006), 065901.

[2] J. F. R. Archilla, J. Cuevas, M. D. Alba, M. Naranjo and J. M. Trillo, *Discrete breathers for understanding reconstructive mineral processes at low temperatures*, J. Phys. Chem. B, **110** (2006), 24112.

[3] E. Ben-Jacob and P. Garick, *The formation of patterns in non-equilibrium growth*, Nature, **343** (1990), 523–530.

[4] I. P. Chernov, A. P. Mamontov, A. A. Botaki, P. A. Cherdantsev, B. V. Chakhlov, S. R. Sharov, Yu. A. Timoshnikov and L. A. Filipenko, *Anomalous effect of small doses of ionizing radiation on metals and alloys*, Radiation Effects, **97** (1986), 155–160.

[5] D. R. Collins and F. M. Russell, *Computer modelling studies of solitons in layered silicates*, in "6th Int. Conf. Physics Computing, Lugano, Aug. 22-26," 1994.

[6] J. Cuevas, C. Katerji, J. F. R. Archilla, J. C. Eilbeck and F. M. Russell, *Influence of moving breathers on vacancies migration*, Phys. Lett., **315** (2003), 364–371.

[7] V. Dubinko, *Breather mechanism of void ordering in crystals under irradiation*, to be published in: Nucl. Inst. and Meth. in Phys. Research B, (2009).

[8] V. I. Dubinko, A. G. Guglya, E. Melnichenko and R. Vasilenko, *Radiation-induced reduction in the void swelling*, J. Nuclear Materials, **385** (2009), 228–230.

[9] LANF was proposed in 2002 by F. M. Russell in private discussions with J. C. Eilbeck. Patent applications were filed on 2/05/2005 at the UK Pat. Office.

[10] X. Z. Li, B. Liu, Q. M. Wei, S. X. Zheng and D. X. Cao, *Chinese view on summary of condensed matter nuclear science*, J. Fusion Energy, **23** (2004), 217–221.

[11] J. L. Marín, J. C. Eilbeck and F. M. Russell, *Localized moving breathers in a 2-D hexagonal lattice*, Phys. Letts. A, **248** (1998), 225–229.

[12] J. L. Marín, J. C. Eilbeck and F. M. Russell, *2-D breathers and applications*, in "Nonlinear Science at the Dawn of the 21th Century" (P. L. Christiansen and M. P. Soerensen, editors), Springer, Berlin, (2000), 293–306.

[13] J. L. Marín, F. M. Russell and J. C. Eilbeck, *Breathers in cuprate-like lattices*, Phys. Letts. A, **281** (2001), 21–25.

[14] Yu. V. Martynenko and P. G. Moscovkin, *Solitons in radiation physics of crystals*, Rad. Eff. Def. Solids, **117**, (1991), 321–328.

[15] G. H. Miley, H. Towner and N. Ivich, "Fusion Cross Sections," Report COO-2218-17, Uni. of Illinois, Urbana, `http://home.earthlink.net/~jimlux/nuc/sigma.htm`.

[16] D. M. Newns and C. C. Tsuei, *Fluctuating Cu–O–Cu bond model of high-temperature superconductivity*, Nature Physics, **3**, (2007), 184–191.

[17] F. M. Russell, *Identification and selection criteria for charged lepton tracks in mica*, Nucl. Tracks Radiat. Meas., **15** (1988), 41–44.

[18] F. M. Russell and D. R. Collins, *Lattice-solitons and non-linear phenomena in track formation*, Radiation Measurements, **25** (1995), 67–70.

[19] F. M. Russell and D. R. Collins, *Lattice-solitons in radiation damage*, Nucl. Insts. and Methods B, **105** (1995), 30–34.

[20] F. M. Russell and D. R. Collins, *Anharmonic excitations in high Tc materials*, Phys. Letts. A, **216** (1996), 197–202.

[21] F. M. Russell and J. C. Eilbeck, *Evidence for moving breathers in a layered crystal insulator at 300k*, Europhysics Letters, **78** (2007), 10004.

[22] F. M. Russell, Y. Zolotaryuk, J. C. Eilbeck and T. Dauxois, *Moving breathers in a chain of magnetic pendulums*, Phys. Rev. B, **55** (1997), 6304–6308.

[23] P. Sen, J. Akhtar and F. M. Russell, *MeV ion-induced movement of lattice disorder in single crystal silicon*, Europhys Lett, **51** (2000), 401–406.

[24] R. H. Silbee, *Focusing in collision problems in solids*, J. Appl. Phys., **28** (1957), 1246.

[25] J. W. Steeds, F. M. Russell and W. J. Vine, *Formation of epidote follil positron tracks in mica*, Optik, **92** (1993), 149–154.

Received September 2009; revised November 2009.

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