Structure in mobile discrete-particle nonlinear lattice excitations.

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15 February 2012

Mica as a detector of events at the atomic level.

The discovery that natural crystals of muscovite mica could record permanently the passage of charged particles opened a new way to study the interaction of swift particles with crystalline materials.[1] This was possible for two reasons. Firstly, mica is transparent and can be cleaved easily in to thin sheets thus enabling study of processes usually hidden within the body of a crystal. Secondly, the recording process involves precipitation of an impurity of iron as the black mineral magnetite, Fe_3O_4, at sites of lattice disturbance, thereby revealing both transient and permanent changes to the lattice. The impurity, mainly of iron up to a maximum of about 1.7 atomic percent, is incorporated in to crystals during their growth deep underground.[2] A unique feature of the recording process is the ability to record the development and propagation of uncharged transient lattice excitations. A contributing factor is the quasi-two-dimensional behaviour of the crystal due to the recording process being limited to mono-atomic sheets of potassium atoms with the large atomic spacing of about 0.5nm. This unusual spacing results in a spreading out of the disturbances due to the reduced atomic and thus nuclear volume density. Also, the mirror silicate slabs either side of the potassium sheet encourage channelling of charged particles. Although all the recorded tracks and other transient events occurred many millions of years ago the physical processes and particle interactions involved have not changed over time. The apparent disadvantage that the recording process is not under laboratory control is more than offset because of the great diversity of events that Nature offers spontaneously.

Tracks of charged particles and uncharged lattice excitations.

The various disturbances to the lattice, due mainly to external influences such as cosmic rays and internally due to radioactive decay of potassium nuclei, leads to a bewilderingly complex array of intersecting black lines and dots. See figure 1. In addition, crystals sometimes suffer fractures due to local movement of the rock matrix. It was noted in preliminary studies that most of the lines were parallel to main crystal directions but a few lay at random directions in the (001)-plane of the potassium sheets. Measurements on these random lines showed them to be the tracks of high energy muons, most probably created by neutrino interactions in the Earth. This established the remarkable sensitivity of the recording process. Measurements on the much shorter tracks due to positrons emitted from the decay of potassium K^{40} nuclei within the mica crystals confirmed that charged particle tracks could be recorded. The majority of the lines, however, remained of unknown origin until it was observed that they could be created by scattering of a muon but not of a positron. This pointed to transfer of momentum as an essential factor and led to the discovery of tracks due to highly localised, mobile, uncharged, nonlinear lattice excitations involving longitudinal optical mode motions of atoms within the envelope of the excitation.[3] These were subsequently found to be described well as a type of self-focussing intrinsic localised mode called a breather.[4] Breathers, like phonons, can be acoustic or optical mode with either transverse or longitudinal motions. For most practical purposes in radiation damage work longitudinal optical mode breathers are involved as transverse optical mode breathers degrade quickly. To specify this type of breather, as optical mode breathers have the highest energy, and to reflect the quasi-one-dimensional nature of these excitations the term quodon was introduced.

Unexplained patterns.

At an early stage in studying the tracks of muons in mica crystals it was observed that numerous **fan**-shaped appendages originated from the tracks, as seen in Figure 2. This is a negative image so the black magnetite appears white. Their origin was consistent with multiple scattering events creating atomic cascades but their range of about 1mm was inexplicable as cascades are known from molecular dynamic studies to be of only a few tens of nanometre scale. The linear extent or range of these patterns eliminated the possibility that they were the tracks of charged particles associated with atomic cascades. Moreover, other mica crystals showed similar fan-shaped patterns but of two orders of magnitude greater scale and range. An example is shown in Figure 3. Studies of these exceptionally long fans showed that they contained an inner structure of multiple parallel lines that resembled tracks of quodons. Although these multiple lines lay in principal crystallographic directions as do quodons they are, in fact, inconsistent with a quodon origin. Basically, quodons are solitary objects and become unstable if two or more are in very close proximity. Hence, it is concluded that some other kind of nonlinear lattice excitation exists.

Estimate of energy in a fan.

It is reasonable to assume that the minimum energy of atomic motion needed to trigger or initiate the recording of this novel excitation is similar to that for quodons. Since the recording process is not triggered by spontaneous pile-up of phonons the minimum energy for recording must exceed ~0.1eV. As the maximum width of the narrowest envelopes of fans in Figure 2 is ~0.1mm the number of atoms at the front of the disturbance is of order $\sim 2.10^5$, suggesting an initial total energy of 20keV. This is a reasonable fraction of the total energy in a typical atomic cascade.

Not previously reported.

In view of the significant amount of energy in this novel excitation and its great range it is reasonable to ask why it has not been reported before. Basically, other than by the unique recording process in muscovite crystals there is no known way to detect and locate a highly localised uncharged lattice excitation within a crystal. The small change in temperature of a crystal due to the eventual degradation of the excitation to phonons might be used but would indicate little or nothing more. Photographic and bubble chamber detectors do not have long range ordering of a lattice so mobile lattice excitations could not exist in them. However, it is possible that transient electric fields might be detected if the excitation was created in a piezoelectric crystal.

Energy loss by electronic and nuclear scattering.

The rate of energy loss by high energy or relativistic muons in an amorphous material of the same stopping power as mica is reported at about 5MeV/cm. Allowing for the low nuclear volume density in the potassium sheets reduces this by a factor of ~100 and planar channelling contributes a further factor of ~10, giving dE/dx ~20keV/cm for muons moving in the vicinity of the potassium sheets. Figure 1 indicates that about 3 cascades are created per cm of muon track. **Hence, the common assumption that at high energies the main cause of energy loss by a charged particle is via electronic routes appears unreliable in crystalline materials.**

Conclusion.

The fan-shaped patterns in mica show that some kind of mobile uncharged lattice excitation is created during the development of atomic cascades due to nuclear scattering of swift particles. The internal structure of this excitation consists of multiple lines lying in atomic chain directions. This points to some kind of nonlinear lattice excitation that is stable against thermal motion and point lattice defects but different from quodons or breathers. One suggestion is that the excitation consists of multiple kink solitons.

References.

1.F M Russell. Identification and selection criteria for charged lepton tracks in mica. *Nucl. Tracks Radiat. Meas. 15:41-44, 1988*

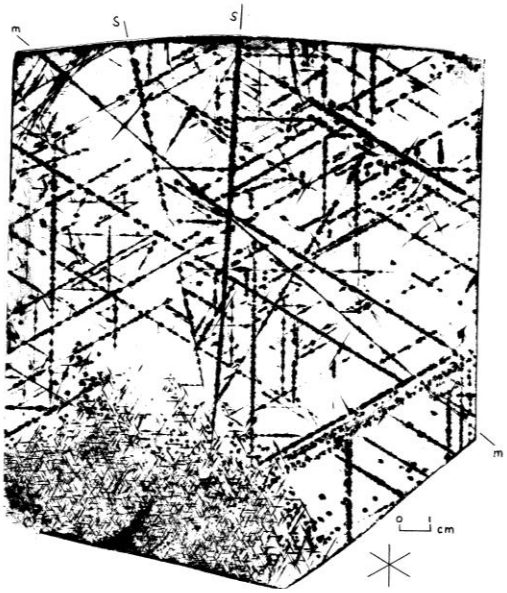
2. Zussman et al, Silicate Minerals, micas.

3.F M Russell and D R Collins, Lattice-solitons in radiation damage. *Nucl. Insts.& Methods. B, 104:1-4,1995*

4. J L Marin, J C Eilbeck & F M Russell, Localised moving breathers in 2-D hexagonal lattice. *Phys. Letts.* A, 1998

Example of lines in mica

Thin sheet (0.2 mm thick) from a single crystal.



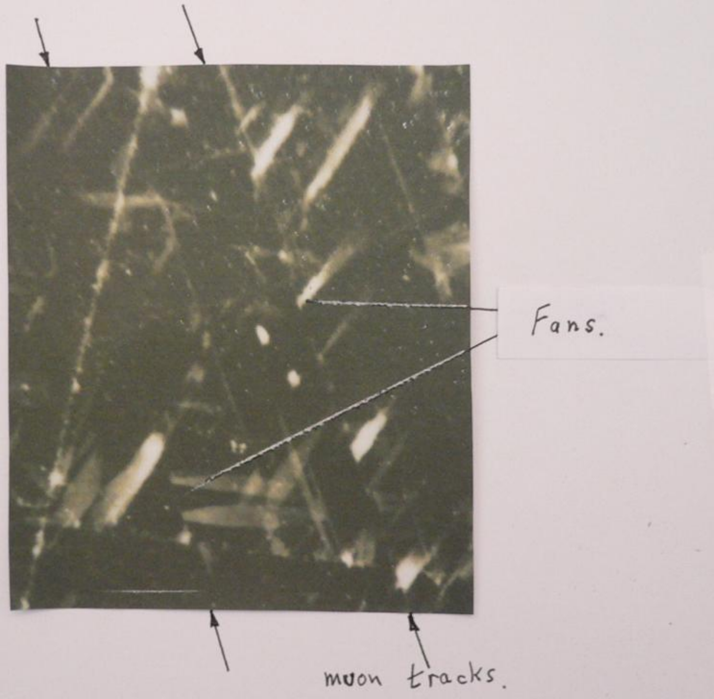


Fig. 2

Figure 3. A lattice excitation that starts from an atomic cascade. It looks something like a shock wave but contains an unexplained inner structure.