Intrinsic localized modes in polymers and hyperconductors

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The history of the experimental study of nonlinear lattice excitations in layered silicate materials when exposed to swift particles of appreciable momentum is described briefly. For brevity, and because of the difficulty of studying the structure of the lattice excitations, the term quodon was adopted to reflect their ballistic and quasi-one-dimensional propagative nature. Quodons in muscovite were observed experimentally. Eventually, it was deduced that the lattice excitations were carrying electric charge. This led to the prediction of hyperconductivity (HC) in which charge is carried ballistically by neutral, mobile lattice excitations in absence of a driving electro-motive force and at any temperature. HC was later observed experimentally. For practical applications of HC, it is necessary to encase the HC material in an insulating sheath. This focussed attention on the behaviour of insulating materials in the presence of quodons. These could enter the sheath by direct contact with the HC material or by impact of the swift particles. It was found that quodons can exist and propagate in many different materials, perhaps all, but their behaviour can vary dramatically. This universality and charge neutrality, together with their unexpected existence in the excellent insulator polytetrafluoroethylene (PTFE), probably accounts for the delay in finding evidence of their existence.

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I. INTRODUCTION

In this section we describe briefly previous findings on fossil tracks in silicates by swift particles and nonlinear excitations called quodons, which can carry electric charge, and the phenomenon of hyperconductivity, i.e., the transport of charge in absence of an electric field and the difficulties on constructed hyperconducting cables. A recent review summarize the main facts on tracks and hyperconductivity [1]. We also compare quodons with other nonlinear excitations and introduce hypotheses about the nature of their extraordinary properties.

A. The study of fossil tracks in muscovite crystals

The finding that sub-relativistic positrons from the decay of ^{40}K [2], in the layered silicate muscovite, can generate a fossil track, composed of magnetite, of up to 10 cm length in the mono-atomic (001)-plane of potassium [1, 3, 4], led to a study of the angular distribution of the fossil tracks in that plane [3]. That led to the finding of similarly long narrow ribbons composed of epidote that originated from the decay site giving rise to the positrons [5]. However, these ribbons lay exactly in a principal crystallographic direction in the opposite direction to the positron tracks [5]. This prompted study of the lattice dynamics involved in the decay process and the prediction of mobile, highly localized, discrete-breathers [6, 7], arising from nonlinear lattice excitations [8, 9]. Quodons travelling along lattice directions in the cation sheet of muscovite were demonstrated experimentally [10]. In turn, this led to the suggestion that these mobile excitations might trap and carry units of positive charge in the (001)-plane [11, 12], the charge arising from the dominant decay channel of ^{40}K[2] when ejecting an electron.

The motion of slowly moving ballistic positive charges should also create fossil tracks composed of magnetite. The first notable feature of these tracks was their exceptional length, of up to 40 cm, limited by size of the crystal [13]. The second feature was their propagation in any of the six principal crystallographic directions in the excellent insulator muscovite in absence of an applied electromotive force (emf) [13]. The third surprising feature was that the tracks were formed when the crystal was cooling at a temperature exceeding 700 K, indicating non-interaction of the mobile excitation with phonons [11].

B. Hyperconductivity

The possibility that energetic mobile lattice excitations might transport charge through muscovite, when the crystal was irradiated with alpha particles from the decay of ^{241}Am, was verified by experiment, suggesting the possibility of hyperconductivity (HC) at any temperature in muscovite [14]. Of special interest, was the finding that the lattice excitations created by swift ions, the

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quodons, could cross random interfaces between sheets of muscovite, thus showing that they could propagate in other directions than in the (001)-plane of muscovite [15]. This suggested a possible way to made a cable, to exploit the ability of transporting charge ballistically at any temperature [16].

However, initial attempts at making an HC cable using muscovite failed. Difficulties arose from inability of obtaining large crystals of high purity, because it cannot be synthesised easily, and from inability to make a flexible cable from sheets of the brittle material. This focussed attention on synthetic fluorphlogopite but high material cost and the same problem of a brittle material made it impractical. A search for a flexible material with pseudo-layered silicate structure led to chrysotile, which has a fibrous nature. To construct a cable, it would be necessary to confine the fibers within an insulating sheath. This led to study of the behaviour of the excellent electrical insulator polytetrafluoroethylene (PTFE) when exposed to irradiation with swift ions that are necessary for the creation of the mobile lattice excitations needed for HC. Here, we report on these studies, the principal finding being that positive or negative charges can be transported through PTFE, in absence of an applied emf, by quodons created by impact of swift ions. Further, the quodons can be created in a metal and then propagate into PTFE.

C. Quodons and other lattice excitations

Quodons are produced by the recoil of beta decay, swift particles and experimentally by alpha bombardment. Alpha bombardment is a simple way of producing nonlinear excitations in a material, however the energy delivered is too large and other procedures would be convenient. Under study is the use of plasma ions with low energy, which potentially could produce a quodon per plasma ion, allowing a much more precise study. So far, it has not been achieved and the charged nature of the plasma particles, electrons and ions, introduce severe complications to measure small currents. Neutral breathers have been proposed to explain the deep annealing of defects observed under low energy plasma exposure [17, 18]. Alpha particles have been proposed as a means of producing crowdions, consisting basically of a moving interstitial and obtained theoretically in the framework of the Frenkel-Kontorova model [19–21]. Supersonic crowdions have been described in one-dimensional models [22–24] and three-dimensional molecular classical and ab initio molecular dynamics [25, 26]. However, generally speaking, crowdions transport mass but not electric charge. In ionic crystal they do transport mass and charge, but this charge, being an ion, can not be transmitted to electrical wires and circuits. Quodons do transport electric charge as polarons do [27–29], however, they do not need an electric field to propagate. Therefore, the most likely entity is a soliton [30] or a breather [31], that is, a localized vibration, coupled to an electron or hole. Quodons, initially found in chains of layered silicates and showing ballistic properties have know been observed in very different materials, as described in the present paper, with non ballistic behaviour. The explanation is the capability of breathers to modify Arrhenius law and increase the speed of transition of an electron of hole from an atom or ion to the neighbour with an amplifying factor of the order of $\exp(\Delta V/kT)$, where ΔV represents the change of the transition barrier brought about by the breather, k is the Boltzmann constant, and T, the absolute temperature [32–34].

D. Outline

The article is structured as follows: after the introduction, the experimental setup is decribed in Sect. II. Section III presents the results in PTFE, while Sect. IV introduces the new technique of triple filter for the study of quodons in several materials. The results and their consequences are evaluated in Sect. V. The article is finished with the conclusions.

II. STUDY OF QUODONS: EXPERIMENTAL ARRANGEMENT

A sample of material to be examined is suspended vertically in a Faraday Box (FB), from the input socket of a transimpedance amplifier. Placed below the sample is a source of alpha particles from ^{241}Am impregnated discs contained in a grounded metal gated-enclosure. When the gate is closed no alphas can escape the enclosure.

The fastest time for opening or closing the gate is 0.2 s. After preparing a sample by cutting all faces of a slab of PTFE to remove surface contaminates, a copper wire is inserted into a hole drilled at one end, which provides means for hanging the sample and gives an electrical contact. It can be positioned to touch the gated-enclosure or be suspended above it with a variable air-gap of a few mm thickness. Vertical suspension, instead of horizontal positioning by supporting struts, eliminates leakage of current through the struts to ground, which was found to cause severe degradation of transmitted current through the sample.

These procedures result in the sample gaining a static charge from handling in addition to a distributed charge due to the machining. The experimental arrangement is shown in Fig. 1.

Figure 2 shows the current plot for a sample of PTFE prepared in this way when irradiated with alphas for the first time. It shows four stages in the transport of electrons occurring at different times. These were identified by deliberately introducing charge by additional machining and handling of the sample. The first peak, curve 1, is due to static charge. It can be minimized by wearing appropriate gloves. The second peak, curve 2, is due to machining or physical damage to the sample. The

FIG. 1. The arrangement for supporting a sample by suspension to avoid degradation of transmitted current through supporting struts. The air in the FB is ventilated to minimize ions coupling charge to the sample.

broad third peak of curve 3 arises from the local environment and background radiation. The total charge for curve 3 increases with time and the volume of the sample. The small current observed before alpha irradiation starts, the fourth stage, is due to cosmic radiation and any quodons created within the gated-enclosure that reach the sample via physical contact. Due to quodons annealing defects, the curve 2 is usually absent in subsequent irradiations and the magnitude of curve 3 grows with time approaching a limiting state where the damage and ionization caused by cosmic rays is annealed by the quodons created.

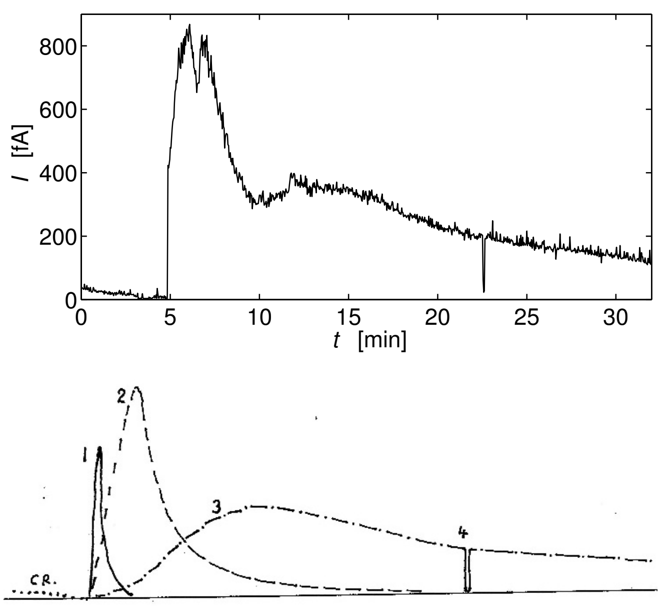

FIG. 2. **(Top)** Plot of transmitted current when sample of PTFE is irradiated with alpha particles for the first time. **(Bottom)** Identification of the underlying causes for the different contributions to the observed current.

III. QUODONS IN PTFE

It has been found that quodons can exist and propagate in many materials. This can lead to misleading results when using conventional current measurement procedures.

The following experiment illustrates the degradation of transmitted current passing through a sample by bleeding of quodons through supporting struts or contacts providing a path to ground. A strip of PTFE, of 67 mm length, 19 mm wide and 7 mm thick, was suspended vertically by a wire attached to the top of the strip and connected to the amplifier input terminal. The bottom of the strip was spaced 1 mm above the grounded alpha gated-enclosure. To minimize charge input to the sample by ions in the surrounding air in the FB, the air in the box was ventilated. This ventilation also reduced the charge fed to the strip via the weak plasma created by the alpha particles as they travelled the 1 mm distance in air to the sample. The strip, which had been previously irradiated to remove initial free charges, was purposely mechanically damaged by drilling four small shallow holes in its side face to introduce new free charges.

As shown in Fig. 3-top, the quodon-current increased rapidly to a maximum of +4200 fA before decreasing asymptotical to a small limiting injected current of about 4 fA. The strip was again mechanically damaged, as before, to create fresh free charges. It was then lowered so that the bottom of the strip was in good contact with the grounded gated-enclosure. When irradiated again the current rose more slowly to a maximum of +800 fA before decreasing to a small limiting injected current. This plot is shown in Fig. 3-bottom.

The decrease in transmitted quodon-current is due to bleeding of quodons to ground, by a factor of nearly 5, illustrating the problem of degradation of transmitted quodon-current due to bleeding of quodons to ground in coaxial cables and connectors in conventional measuring equipment and procedures. The resistivity of PTFE is in the range 10^{23} to $10^{25}\,\Omega\,\mathrm{m}$. The resistance of the samples used for Figs. 2 and 3, measured at a test voltage of 5 kV, was in excess of $7 \times 10^{19}\,\Omega$. To achieve a conduction current of 4200×10^{-15} A would require an emf in excess of 20 MV, which is unrealistic. It follows that an emf resulting from residual injected charge trapped in the sample is many orders of magnitude too small to cause a measurable conduction-current. This is evidence for the charge being carried predominately by quodons.

IV. DEVELOPMENT OF TRIPLE-FILTER TECHNIQUE

These results show that although PTFE inhibits conduction-currents it allows quodon-currents to flow. This provides a means for studying the behaviour of quodons in other materials. Consider the arrangement consisting of two pieces of PTFE that are connected by a

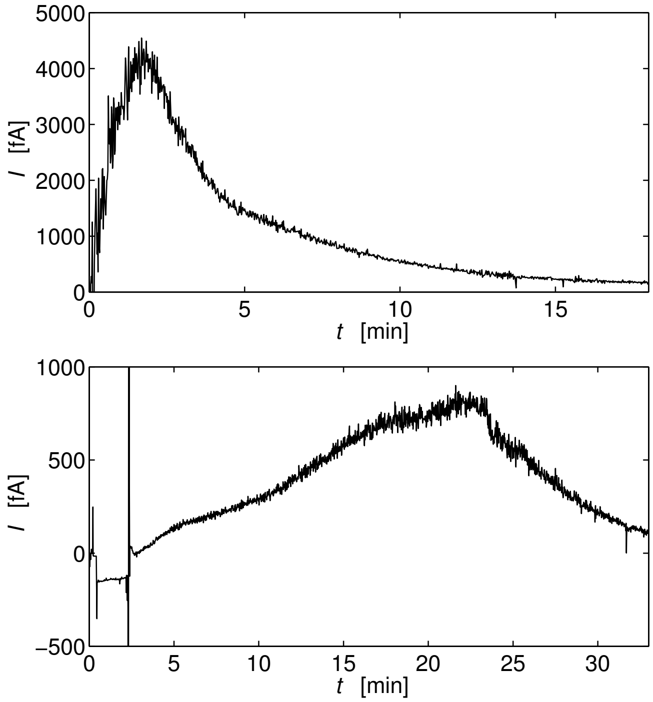

FIG. 3. **(Top)** Plot of current flowing through the strip of PTFE when irradiated with alphas. The peak current was +4,200 fA and then fell asymptotically towards a small limiting current. The strip was again mechanically damaged to create free charges, lowered to be in contact with the grounded gated-enclosure, and irradiation restarted. **(Bottom)** The quodon-current rose more slowly to a lower maximum of +800 fA before decreasing to a small injected current.

length of copper wire. This triple-filter is hung vertically with the bottom face in contact with the grounded alpha gate-enclosure. The upper end face is connected to an amplifier. The current flowing through this triple-filter when irradiated with alphas is shown in Figure 4.

Although copper is a good conventional conductor, the first piece of PTFE prevents any conduction current reaching it. Current can only flow through the second piece of PTFE when carried by quodons. Hence, within the copper, either quodons propagate through it or they are regenerated at the interface with the upper piece of PTFE. This triple-filter has been used with many different materials replacing copper. These ranged from metals, semiconductors, inorganic crystals of various lattice structures, amorphous solids like glass, organic polymers, Bakelite, wood and even water. In each case, quodons-currents were found to propagate through the triple-filter. This suggests quodons adapt to the local atomic structure to conserve energy and momentum.

In each case, the maximum alpha flux exiting from the gated-enclosure was limited to an average of about 2000 per second. The maximum negative current fed to a sample by the alphas, if fully ionized, via the injected charge is about -0.6 fA. This can be altered by current passing through the alpha-generated plasma if there is an emf existing or created within the gated-enclosure. The maximum quodon-current observed in a sample was about +60000 fA. On the basis of a quodon carrying only one unit of charge, this required 6.2×10^3 quodons for each femto-amp of transmitted current. Hence, each alpha particle, on average, creates about 2×10^5 quodons, each of about 25 eV energy. This is comparable to the energy released in the decay of 40 K, 42 eV, when emitting an electron, that started the study of quodons. Further, the alphas impacting on the interior of the gated-enclosure will also create quodons. These will reach any material placed in contact with the enclosure and can contribute to the very small currents observed before the gate is opened. Cosmic rays, especially muons, will also create quodons leading to random sharp spikes of current as well as radiation damage.

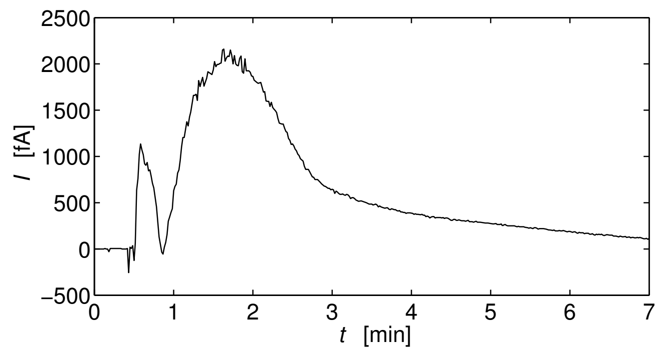

FIG. 4. The quodons penetrate through the triple-filter within 1 sec. The first peak is sweeping of static charge. That is followed by capture of free charges by quodons, reaching a peak of +2000 fA.

V. DISCUSSION

The triple-filter technique is a paradigm shift for studying the existence and propagation of quodons in any material. The finding that quodons can be created and propagate in the excellent electrical insulator PTFE, and also in other high-quality insulators such as Mycor and polyethylene, highlights the problem of degradation of quodon-currents in conventional electrical equipment. This would contribute to the apparent lack of interest in, or recognition of, the existence of quodons in most equipment involving swift particles or ions. Although quodons would be expected to occur in most such systems, their main effect would be benign, to anneal lattice defects and remove free charges. Only in special lattices showing planar characteristics would their ability to propagate ballistically be evident.

The bleeding of quodons through supports poses a practical problem in connection with countering gravity for studying samples. In addition to vertical suspension of samples, another successful method is by magnetic levitation of the quodon-carrying sample. Since quodons involve atomic interactions, albeit at unusually high energies, it is not too surprising that they can exist in all materials so far examined. The difficulty of inhibiting their propagation is reminiscent of the task of stopping transmission of heat in physical structures. Another unresolved problem is how might quodons interact with integrated micro-electronic devices. Since the triple-filter technique showed that they can exist and propagate in silicon, they might act mainly to slightly degrade signals.

The assumption that a quodon can trap only one unit of charge is supported by the fact that the widths of the fossil tracks of quodons carrying a positive charge in muscovite shows no evidence of doubling or halving even after travelling 10^9 unit cells through the crystal.

Evidence for quodons was found first in the fossil tracks in muscovite, created by the swift recoil of calcium or argon atoms arising from radioactive decay of 40K. Experimental evidence for their existence was found using swift alpha particles from 241Am, which created energetic excitations in atomic cascades. There was also evidence for their creation in atomic cascades resulting from nuclear scattering of relativistic muons. The essential requirement for their creation is nonlinear interaction between kinetically energetic atoms and not directly by the mass or energy of the primary swift particle. Hence, it is expected that quodons will be created via atomic cascades produced by swift protons. This raises the subject of the possible role of quodons in proton-beam-therapy of tumours. Initial trials on quodon propagation in flesh using the triple-filter technique are encouraging.

CONCLUSION

The apparent ubiquitous existence and propagation of quodons in many different materials, especially in the excellent electrical insulator PTFE, impeded analysis of the electrical response of polymers when irradiated with swift particles. Development of the triple-filter technique, which enabled separation of conduction-currents from quodon-currents, allowed the causes of variation of current observed in time-plots of transmitted current under constant irradiation conditions to be determined. The results revealed the difficulty of inhibiting the propagation of quodons, with implications for development of HC cables. However, early numerical modelling of the behaviour of discrete particle breathers in layered silicates showed evidence of total internal reflection of breathers at crystal surfaces. Preliminary studies of this effect have indicated a possible practical solution that could be applied to HC devices.

Finally, the well know degradation of energy of swift particles in matter via atomic-cascades indicates that quodons will be produced copiously during proton-beam-therapy. The possibility of high quodon fluxes breaking bonds in organic molecules or assisting healing at lower fluxes needs to be examined further.

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