Final Report Summary - SUPERSOLID (THE ENIGMA OF SUPERSOLIDITY)

Sometimes, one searches for something and one discovers something else. This is what happened to us[1]. We were looking for a paradoxical phenomenon called "supersolidity" that is the surprising coexistence of elasticity and superfluidity in a quantum solid. Our initial motivation came from the observation by E. Kim and M. Chan (Penn State University in 2004) that helium 4 crystals did not seem to rotate at low temperature like a normal solid[2]. Their observations had been reproduced in half a dozen of laboratories throughout the world and presented as a possible evidence for supersolidity. But no consensus could be reached about this interpretation [3,5,9]. Thanks to a generous ERC grant, we discovered that, in reality, what takes place in these helium 4 crystals is not supersolidity but a “Giant plasticity” [6,11]. As any ordinary crystal, helium 4 crystals contain linear defects called “dislocations”. But the dislocations move so easily at low enough temperature and in the absence of impurities that the crystals do not resist to shear in one particular direction, somehow like a pile of paper for a printing machine, where paper sheets may glide against each other without much friction. Even more easily, actually.

It is well known in Materials Sciences that the deformation of crystalline solids proceeds from the displacement of their dislocation lines. The crystal planes cannot move as a whole, they move line by line thanks to these linear defects. However, in classical crystals, the periodic structure leads to so-called “Peierls barriers” against this motion. As a consequence, high temperatures and large stresses are necessary for dislocations to move. To bend a copper tube one needs to warm it up and to apply a strong force. This is to overcome these barriers. In a quantum crystal where the Heisenberg uncertainty principle leads to large fluctuations in the position of atoms, these barriers may be small and the dislocations may move by quantum tunnelling. This is what we have discovered. Down to extremely low temperatures (15 millikelvin) and even with stresses of order nanobars (100 billion times less than the typical value of the elastic modulus which is the ratio between the applied stress and the resulting strain), we have demonstrated that helium 4 crystals deform without measurable dissipation[6, 11, 12, 15, 17, 21]. But there are two conditions for this spectacular nano-deformation to occur: no pinning of dislocations by impurities, and no scattering of the moving dislocations with the thermal fluctuations called “thermal phonons”. We studied helium 4 crystals very close to the absolute zero that is 0 K = -273.15°C, actually down to -273.14°C. At such ultralow temperatures, there remains only one kind of impurity in these crystals, the light isotope helium 3 atoms, and we have actually found a method to reduce their concentration from 10^-7 (one part in 10 Millions) down to 10^-12 (which can still be measured) and finally to zero [19, 20, 22, 23].

In fact, helium crystals are known to be model systems due to their very high purity[13, 16, 21]. It is well known in metallurgy that dislocations are pinned by impurities and that the motion of dislocations dissipates energy. The possibility to study such phenomena in a limit of low temperature and extreme purity gave us access to quantities that are usually hard to disentangle from other phenomena. With helium 4, he role of dislocations in the mechanical properties of a crystal is spectacular and clearly identified. Thanks to careful optical control of the growth of high quality oriented single crystals[11], we could identify the direction in which dislocations are able to glide[11], then to analyse the effect of impurity pinning and that of interactions with thermal phonons[12]. From this analysis, we could deduce the dislocation density in crystals of variable quality[12, 19], the topology of the dislocation network[12] (they are aligned parallel to each other in planar “sub-boundaries”), the average
length between nodes in this network and later the distribution of these lengths (from tens to hundreds of microns)[17], the velocity at which they move, the binding energy of helium 3 impurities to dislocations (0.7K) and then the distribution of this energy (0.1K around 0.7K) which depends on the edge or screw character of the dislocations[17]. This is a vast and unique set of physical quantities characterizing dislocations in this model crystal.

Eventually, we discovered an astonishing phenomenon that occurs in no other crystal. Dislocations may move at high speed (up to 10 m/s at kHz frequencies!). Now, under small enough driving strain so that their velocity is less than 45 microns/s, they move with mobile helium 3 impurities attached to them[14, 20, 23]. In this case, the dressed dislocation is a kind of atomic necklace with helium 3 pearls, so that it moves with a small friction on the periodic lattice. We proposed that this dissipation of energy comes from the emission of transverse waves along the dislocation line, as when one pulls a pearl necklace on a washboard or when one agitates a rope[20, 23].

This set of measurements makes the mechanical properties of helium 4 crystals of universal interest in Materials Science and, at the same time quite original if not spectacular due to the quantum character of this system.

During the 5 years of this work, we also understood and explained why the elastic anomaly of helium 4 crystals is the true explanation of what had been erroneously presented as "evidence for supersolidity"[4, 7, 8, 10]. If it exists, supersolidity will have to be found in another quantum crystal.

References (all attached to this ERC grant, except ref.2)

5- S. Balibar, "Is there a true supersolid phase transition ?", Physics 3, 39 (2010).

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