Collective Behaviour and Glassiness in Complex Quantum Systems

A tale for the uninitiated

We are used to thinking of solid matter as rather pure materials forming regular crystals. However, many materials in real life and in the physics laboratory are far from clean, and often deliberately so. In such systems *disorder* (e.g., impurities in a crystal) plays an essential role and crucially determines physical properties. For example, a metal with a good electrical conductivity can be turned into an insulator upon introducing a sufficient amount of disorder. The mechanism by which this happens is known as *localisation*. The electrons in pure metals behave essentially like matter waves which flow over the regular background of the crystal lattice of atoms. Any small electric field immediately creates a current by biasing the flow of the matter waves. However, disorder imprints the regular pattern of the crystal with bumps that partially reflect the electron waves. Once the reflection becomes strong enough the waves are localised and prevented from spreading further across the sample. In this situation the response to an electric field vanishes: the disorder has turned the material into an insulator!

Competing with disorder in insulators is a second important ingredient: the repulsive Coulomb interactions between the electrons. On the one hand, electrons would like to localise in places which are energetically favourable. On the other hand, such localisation generally inhibits the electrons from being well separated from each other, which would better accommodate their Coulomb repulsion. This sort of competition very often occurs in disordered systems and is referred to as *frustration*. Frustration entails complex physical behaviour which gives rise to a plethora of exciting new phenomena not present in clean systems. In the absence of disorder, interacting electrons tend to arrange themselves into a regular lattice (a so-called Wigner crystal). This is an essentially unique pattern which can form very readily. In the presence of disorder, however, the electrons can settle in many different configurations all of which are "locally stable", meaning that no single electron can move individually to a different location to reduce the internal strain. Only by rearranging electrons *collectively* is the system actually able to relax. This slows down the dynamics significantly, as is seen experimentally in a very slow decrease of the electrical conductivity over time. At a sufficiently low temperature, full relaxation may occur so slowly that it will never be fully achieved: A so-called *glass* forms. Such glasses exhibit a lot of intriguing properties: They never reach their equilibrium state, but keep evolving. The longer the system spends relaxing, the slower the dynamics become - a phenomenon called ageing. Moreover, glasses remember their history over remarkably long periods, which leads to striking memory effects (e.g., it is possible to tell how long a system has been relaxing under certain experimental conditions by measuring a fingerprint of its actual properties).

All these interesting features only appear at low temperature where the order (the pattern of an electron configuration) can be sustained against thermal motion. At higher temperatures, the glass "melts". However, melting can also occur at low temperature if the *quantum* fluctuations (due to the quantum mechanical nature of the system and Heisenberg's uncertainty principle) are strong enough to destroy the order. In this case, one is dealing with a *quantum glass transition*.

My research program aims at understanding the properties and the out-of-equilibrium behaviour of glasses at low temperatures where quantum fluctuations are dominant. This is motivated by many recent experiments which probe this regime in diverse systems such as electronic glasses, the insulator-to-metal transition, superconductors, and disordered magnets, raising a lot of interesting and challenging questions for theoretical physicists.