**Tuning into Novel Quantum Rhythms**

The inexorable move from order to disorder of the universe defines the concept of time. The universe however does not always move from one state to the other in a simple gradual linear way. The existence of life requires very high levels of order locally but once ordered the living organism becomes an exceptional tool for the disordering of the universe: locally ordered systems can lead to a faster disordering of the overall system. The fascinating emergence of organisation and cooperative phenomena from chaos has been termed ‘order-by-disorder’. A recent work published in Proceedings of National Academy of Sciences (PNAS https://doi.org/10.1073/pnas.1922151117) by Dr Matt Coak and Dr Seb Haines in the group of Dr S S Saxena at the Cavendish Laboratory, University of Cambridge and titled ‘Quantum Critical Phenomena in a Compressible Displacive Ferroelectric’, presents the most comprehensive experimental and theoretical study of order-by-disorder in a solid crystal system to date.

This breakthrough reports discovery of an unexpected quantum phase while elucidating a half-century old theoretical conundrum and highlights that the nature of the unpolarised state in incipient ferroelectrics remains in some respects an enigma. Such 'nearly-ferroelectric' materials are widely used in industry and are model materials for understanding novel quantum effects.

Order-by-disorder in this kind of physical system is possible at the lowest temperatures in the presence of a zero-temperature phase transition, or quantum critical point (QCP). It is under these conditions that the effects of quantum mechanics are most clearly observed. Zero-point energy (ZPE) is equivalent to the Heisenberg uncertainty principle which is a fundamental result of quantum mechanics. The nature of the vacuum and the properties that arise due to ZPE remain one of the greatest unsolved mysteries in physics. The influence of ZPE can be seen in many of the most striking phenomena that have been discovered, for example superconductivity and superfluidity. ZPE plays a crucial role in the behaviour of a QCP and the presence of a QCP leads to behaviour that provides evidence for order-by-disorder in a diverse array of materials. This has been studied for many years in magnetic systems and is also present in the system studied in the current breakthrough – strontium titanate. In the work by Coak et al. the nature of the behaviour of this order-by-disorder phenomenon is systematically observed and an interpretation of this behaviour is successfully applied to the new data.

What is fascinating is that normally, quantum and thermal fluctuations tend to disrupt order. However, in this novel state the tendency towards forming order is enhanced rather than suppressed by such fluctuations. This is a phenomenon for which a number of interesting mechanisms have been proposed and debated over many years but has remained unexplained until now.

This theoretical understanding has at its heart the role of the ZPE and the interplay of this with sound waves in the crystal. At ultra-low temperatures (much colder than the vacuum of space) even this model breaks down and must be improved with the addition of an exotic new state where subtle ripples in the electric properties of
the crystal become dominant - a gentle reminder that this is not the vacuum of space but a highly ordered arrangement of atomic strontium, titanium and oxygen. From a fundamental science perspective, this work is significant because it provides for the first time a clear identification of the nature of the mysterious quantum paraelectric state in quantum annealed displacive ferroelectrics.

A quantum paraelectric arises in cases where ferroelectric or anti-ferroelectric order is frustrated or “annealed” by the effects of quantum fluctuations in the local electric polarization. In the magnetic analogue, quantum melting gives rise to a number of possible quantum spin liquid states that have been of great interest for many years and in some cases are connected with a phenomenon of unconventional high temperature superconductivity.

The study of quantum paraelectricity is only in its infancy and is emerging as an important frontier leading to new discoveries and concepts. In particular, the authors show conclusively that the conventionally accepted view of the quantum paraelectric state applies only at elevated temperatures. Below a crossover temperature, controllable with pressure, a new state emerges. This is a crucial insight, as this class of materials are widely and increasingly used as a component for, among many other uses, low temperature sensors.

This work has resolved the long-standing question on the nature of the quantum paraelectric state and shown how the behaviour of this new state evolves as one tunes away from quantum criticality. It has gone on to probe the limits of the theory and shown where the new regimes begin to dominate and presents the first definitive temperature versus quantum tuning parameter (here, pressure) phase diagram of a displacive ferroelectric - a phase diagram that is likely to become the accepted canonical case in the field.

This recent insight and discovery of a new class of quantum transition opens the way for a whole new field of materials physics and quantum technologies research.