Dark matter is commonly expected to be stationary and the Solar System's rotation about the Galactic Centre should carry the Earth through the dark matter domains at around 300 km s^{-1}. Thus, signals from the atomic clock network that propagate at a different speed can be ruled out.

The use of a network of highly responsive sensors for dark matter detection leads to other possibilities. One of the authors has proposed a similar scheme using ultrasensitive atomic magnetometers to search for dark matter fields that couple to the magnetically sensitive spin of an atom[11]. Sensitive force detectors such as gravitational wave detectors may also detect passing changes in potential energy. With detectors in laboratories around the world, the use of coordinated observations could very well lead to new types of astronomy focused on the normally unobservable consequences of local dark matter. ❐

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VORTEX PHYSICS

Ferroelectrics in a twist

Ferroelectric polarization vortices close to a ferroelectric transition turn out to be striking models of the cosmos in which strings are thought to have condensed out of the rapid expansion of the early Universe.

Stephen E. Rowley and Gilbert G. Lonzarich

Topological entities such as vortices (Fig. 1) or skyrmions are often expected to form spontaneously in proximity to many different types of phase transitions including those investigated in cosmology, high-energy particle physics and condensed-matter physics. In the latter, they may be readily observed and controlled in the laboratory, and are seen for example in superconductors, liquid helium, magnets and ferroelectrics. Writing in *Nature Physics*, Shi-Zeng Lin *et al.*[1] describe an ingenious and effective way of observing and understanding vortices in ferroelectric manganates using concepts and techniques at the frontier of the field.

Thermally excited vortex–antivortex pairs (as opposed to those forming in the presence of externally applied fields or rotation) can form and annihilate rapidly and are therefore usually difficult to study directly in liquids. However, in the ferroelectric materials of concern here, vortices can be frozen-in by rapid cooling, allowing them to be studied at leisure using sensitive piezoelectric surface probes and depth profiling techniques. The materials $RMnO_3$ (where R = Lu, Y, Er or Tm, for example) are all ferroelectrics with Curie temperatures (T_C) well above room temperature.

In the high-temperature paraelectric phase, fluctuations of the polarization order parameter are confined to a two-dimensional plane. Due to the details of the crystal structure, they are further confined to point along one of six possible equivalent directions (as in the six-fold clock model). In the ferroelectric phase there is a preference for the polarization vector in each unit cell to point along one of the same six possible directions resulting in a non-zero electrical polarization when averaging over the whole crystal. In the paraelectric phase, spontaneous fluctuations of the polarization do not lead to complete disorder as in the standard mean-field theory, but to short-range order governed by a balance between the energy and entropy. The resulting fluctuations turn out to correspond to lines of polarization vortices in which the polarization vectors twist around, forming vortex tubes that run through the crystal and terminate at the crystal surface. Below T_C the vortex and antivortex lines form bound states that, in three dimensions, are observed as closed vortex loops. These vortex loops are the dynamical imperfections of the ferroelectric state and diminish in number as one approaches absolute zero, where the spontaneous polarization is greatest.

Figure 1 | Like vortices that form in a liquid, the polarization in ferroelectrics or paraelectrics can spontaneously form thermally excited vortex loops or a forest of vortex lines spanning the entire crystal, which Lin and colleagues[1] have been able to map in detail. The long-range hydrodynamic forces between the lines lead to an effective vector potential and a gauge field theory mathematically analogous to that used for a superconductor, containing its own Anderson–Higgs effect and the phenomenon of 'superflow'.

By rapidly cooling a material from a temperature just above the Curie point to room temperature, the vortex lines can be frozen-in for study using piezoelectric force microscopes to map the orientation, shape and number of such vortices. Moreover, Lin *et al.*[1] found that the density of vortices obeys a scaling relationship with the quenching time and transition temperature that is in close agreement with the Kibble–Zurek mechanism, which was developed to describe topological defects such as monopoles or cosmic strings that influence the evolution of the Universe[2]. The experimental results and those of the Kibble–Zurek theory were also confirmed by Monte Carlo simulations of the manganates considered. These ferroelectric materials seem to be beautiful model systems in which a range of ideas, for example, concerning the cosmology of the early Universe, can be tested.

A further point raised by Lin *et al.* that elucidates the ideas above is the fact that the φ^4 field theory of the ferroelectric, where φ describes a two-dimensional polarization vector (involving only short-range interaction terms), can be transformed into a dual (ψ^4) field theory in terms of a new order-parameter field ψ, known as the disorder field, describing vortex lines[1,3,4]. The average value of the vortex line field ψ is finite above T_C and zero below T_C, where vortex–antivortex pairs form bound states. One sees in the transformation process[3,4] how an effective vector potential field **A** arises that couples to the vortex line field ψ, and leads to a free-energy equation that is mathematically analogous to the Ginzburg–Landau equation of a superconductor. The effective vector potential originates from the long-range hydrodynamic interactions existing between vortices. Thus, the dual theory is a gauge field theory describing a type of fluid exhibiting some of the characteristics of 'superflow' above T_C. Coupling to the effective gauge field gives rise to an Anderson–Higgs mechanism in which the gauge field and the Goldstone mode of the ψ field become massive. This state above T_C in the dual theory is known as the Higgs phase. The corresponding phase below T_C is known as the Biot–Savart phase (because the gauge field in this case is massless and the associated interaction is long-range — the Biot–Savart phase is also sometimes called the Coulomb phase)[1,3].

The transformation from the starting φ field to the dual field ψ has been studied in detail[3,4] for the case where φ belongs to the three-dimensional XY universality class such as that used to describe superfluid helium-4. (In this case, the corresponding ψ field then represents spontaneous vortex excitations in the liquid). Interestingly the discrete six-fold clock nature of the polarization in the ferroelectric manganates develops a continuous U(1) XY symmetry close to the ferroelectric critical point[5]. This 'asymptotic symmetry' or 'emergent symmetry' has also been anticipated for certain ferroelectrics with a discrete three-dimensional order parameter[6]. For ferroelectrics and paraelectrics with a polarization free to point in three-dimensional space, it would be fascinating to search for the corresponding thermally excited skyrmions and antiskyrmions in light of these results[7].

We now remark on a possible extension of the ideas discussed here and by Lin *et al.* — which relate to a purely classical phase transition — and consider the corresponding quantum case in which a quantum tuning parameter such as pressure would be used in the low-temperature limit to pass through, for example, a ferroelectric or magnetic critical point[8]. In such cases the dynamics of the fields would be of key importance. A recasting of quantum phase transitions as arising in the dual field theory of topological objects may prove fruitful in our understanding of exotic states of matter such as the non-Fermi liquids observed in numerous metals and quantum critical matter in general.

This study reminds us that when transiting between two different phases, whether classical or quantum, the medium can be full of fascinating structure. The dual theory highlights the fact that many phase transitions, whether in large-scale cosmological phenomena or in tangible materials in the laboratory, may be recast in terms of a field theory of topological entities rather than the conventional order parameter fields commonly used to describe phase transitions. Early detailed studies of other dual theories include those to describe Berezinsky–Kosterlitz–Thouless transitions and lattice gauge theories and have been developed further in classical and quantum contexts in several areas of physics[9,10]. These topological entities have their own exciting behaviour and consequences for physical observables and indeed may be employed in the technologies of the future. ❐

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