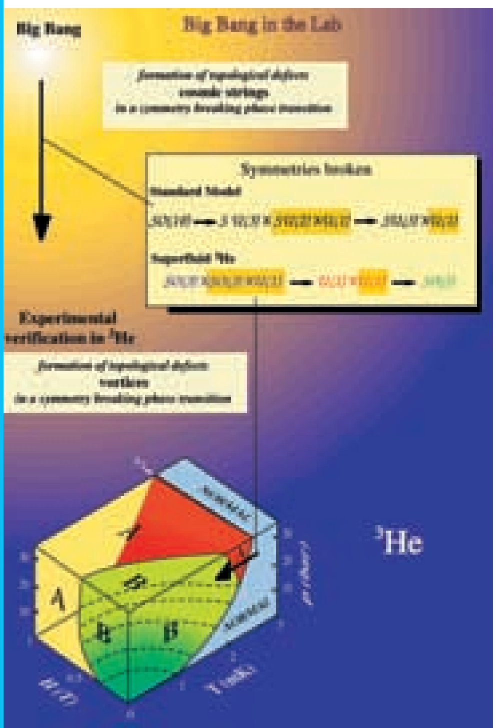
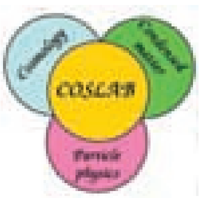
There are fundamental relations between three vast areas of physics: particle physics, cosmology and condensed matter. These relations constitute a successful example of the unity of physics. The fundamental links between cosmology and particle physics, in other words, between macro- and micro-worlds, have been well established. There is a unified system of laws governing all scales from subatomic particles to the Cosmos and this principle is widely exploited in the description of the physics of the early Universe, baryogenesis, cosmological nucleosynthesis, etc. The connection of these two fields with the third ingredient of the modern physics – condensed matter – is the main goal of this programme.

Cosmology in the Laboratory (COSLAB)

An ESF scientific programme





The European Science Foundation acts as a catalyst for the development of science by bringing together leading scientists and funding agencies to debate, plan and implement pan-European initiatives.

This connection allows us to simulate the least understood features of high energy physics and cosmology: the properties of the quantum vacuum. In particular, the vacuum energy estimated using the methods of particle physics is now in huge disagreement with modern cosmological experiments. This is the famous cosmological constant problem. An advantage of condensed matter is that it is described by a quantum field theory in which the properties of the vacuum are known from first principles. This could give an insight into trans-Planckian physics and thus help in solving the cosmological constant problem and other outstanding problems, such as the origin of matter-antimatter asymmetry, formation of the cosmological magnetic field, problem of the flatness of present Universe, the physics of the event horizon, etc.

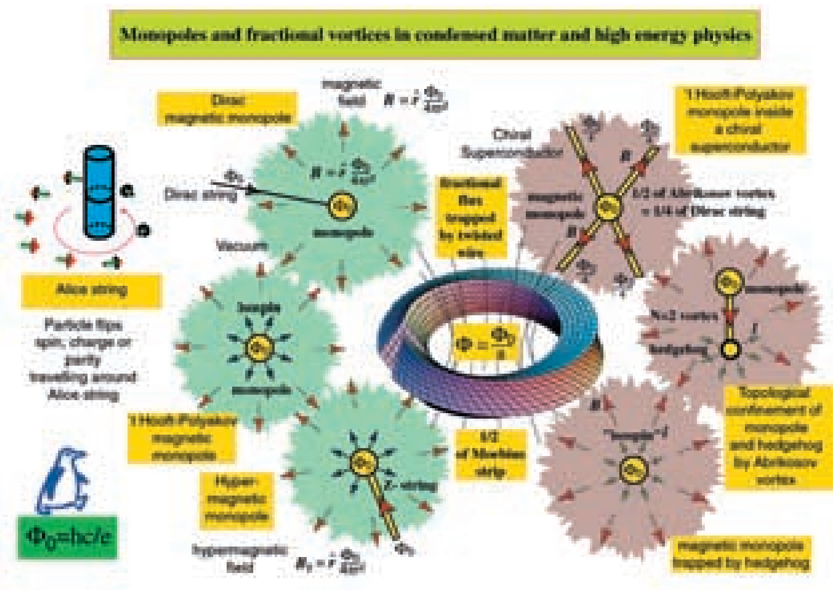
Just as the symmetry is often broken in condensed matter systems at low temperature, it is believed that the Universe, evolving from the initial hot Big Bang, would have undergone a series of symmetry-breaking phase transitions. One of the consequences of the symmetry breaking is the existence of topological defects. Cosmic strings, monopoles, domain walls and solitons, etc., have their counterparts in condensed matter. The topological defects formed at early-Universe phase transitions may in turn have cosmological implications. To test these ideas the condensed-matter systems can be exploited.

(i) the collective modes; (ii) the dilute gas of the particle-like excitations – quasiparticles – which play the role of elementary particles; and (iii) topological defects. The dynamics of collective modes, quasiparticles and defects is described within what we call now 'the effective theory'. In superfluid ^{4}He, for example, this effective theory incorporates the collective motion of the ground state – the superfluid quantum vacuum; the dynamics of quasiparticles in the background of the moving vacuum; and the dynamics of the topological defects – quantized vortices interacting with the other two subsystems.

Such an effective theory does not depend on details of microscopic (atomic) structure of the condensed matter. The type of the effective theory is determined by the symmetry and topology of the ground state, and the role of the microscopic physics is only to choose between different universality classes on the basis of the minimum energy consideration. Once the universality class is determined, the low-energy properties of the condensed matter system are completely described by the effective theory, and the information on the underlying microscopic physics is lost.

Introduction

Quantum condensed matter systems, such as ^{3}He and ^{4}He quantum liquids, superconductors, and magnets, comprise strongly correlated and/or strongly interacting quantum elements (atoms, electrons, spins, etc.). Even in its ground state, such a system is usually a rather complicated object, whose many body physics requires extensive analytic and numerical simulations. However, when the energy scale is reduced, one cannot any more resolve the motion of isolated elements. The smaller the energy the better is the system described in terms of



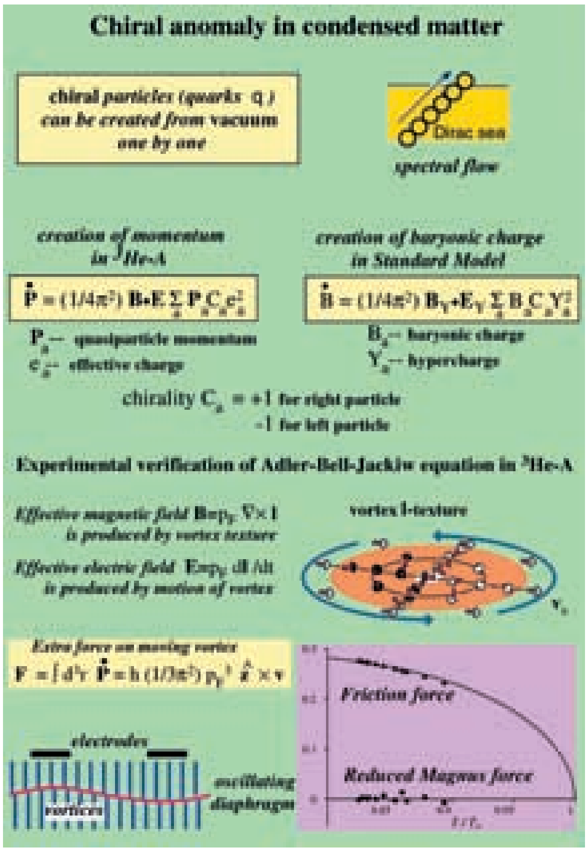
Point defects or monopoles and line defects carrying fractional quantum numbers suggested in particle physics models can have their counterparts in condensed matter. Unconventional superconductors can trap magnetic flux equal to a fraction of the flux quantum of an Abrikosov vortex. In chiral superconductors, magnetic monopoles and their condensed matter partners may be connected by strings or line defects carrying integer or fractional magnetic flux.

In a modern viewpoint the Standard Model of the electroweak and strong interactions, and general relativity are also effective theories describing the low energy phenomena emergently arising in the quantum vacuum. Here again, the nature and physical structure of this medium – the quantum vacuum – on a “microscopic” trans-Planckian scale remains unknown. On the other hand, in condensed matter systems of some universality classes the effective theory resembles very closely a relativistic quantum field theory. For example, the effective theory of superfluid ^{3}He-A reproduces many features of the Standard Model and general relativity: the collective fermionic and bosonic modes there are the counterparts of chiral fermions, gauge and gravitational fields. In addition this superfluid liquid contains a variety of topological defects, which are in many respects similar to the cosmic strings, magnetic monopoles and domain walls appearing in relativistic quantum field theories.

The conceptual similarity between high energy physics and condensed matter systems allows us to use condensed matter as a laboratory for the simulation and investigation of the most intricate properties of the quantum vacuum. We hope that condensed matter can show us the possible routes from our present low-energy corner of the effective theory to the “microscopic” physics at Planckian and trans-Planckian energies.

Scientific background

Common concepts in high energy physics and in condensed matter imply that there are analogous phenomena in both systems, which are sometimes described even by the same equations. One can use this for simulation of cosmological phenomena in the Lab.



In modern theories of particle physics the matter-antimatter asymmetry of Universe is explained in terms of the anomalous production of baryonic charge from the Dirac sea in the early Universe. The equation derived by Adler, and Bell and Jackiw, which describes the anomalous production of baryons, is also applicable to ^{3}He-A, where the chiral anomaly results in the production of the quasiparticle momentum. This leads to an extra force acting on a continuous vortex-texture moving in superfluid. The Adler-Bell-Jackiw equation has been experimentally verified by measurement of the reduction of the Magnus force due to spectral flow (Bevan, et al, Nature 386 (1997) 689, in the Figure the friction force and the effective Magnus force are in units of the nominal Magnus force).

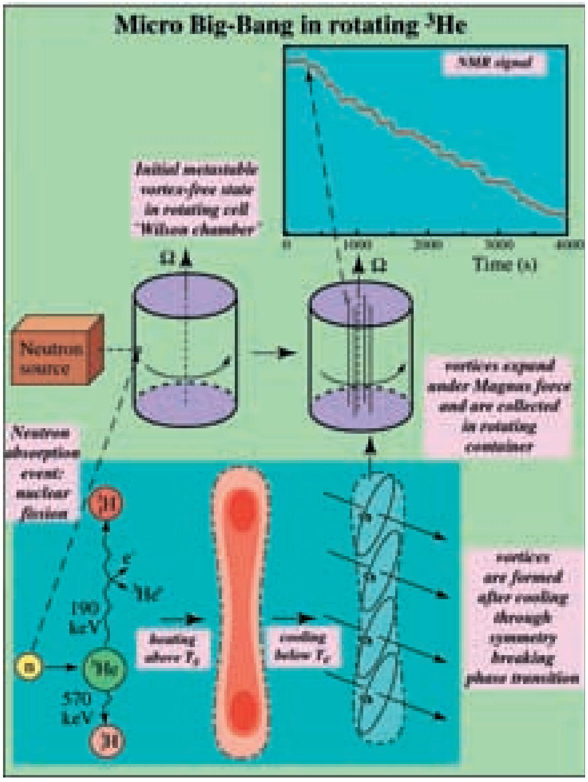
Electroweak baryoproduction and magnetogenesis

Two examples are provided by the phenomenon of the axial anomaly. This phenomenon may in particular be responsible for the production of baryons from the vacuum in the Standard Model, thus explaining the baryonic asymmetry of the present Universe. It is described by an equation derived by Adler, and Bell and Jackiw. It appears that the same physics of axial anomaly occurs in quantum liquids and superconductors resulting in an extra force acting on a moving quantized vortex. The anomalous process of the transfer of the linear momentum from the superfluid/

superconducting quantum vacuum to the vortex is described by the same Adler-Bell-Jackiw equation. The latter was verified in experiments on the vortex dynamics in superfluid ^{3}He performed in the low-temperature laboratory in Manchester, and thus the modern mechanism of the cosmological baryoproduction has been simulated. In the same manner the popular electroweak mechanism of the nucleation of the primordial cosmological magnetic field, also based on the phenomenon of axial anomaly, has been reproduced in the low-temperature laboratory in Helsinki.

Defect formation

The early Universe is believed to have undergone a sequence of rapid symmetry-breaking phase transitions, with emergent consequences such as the formation of topological defects which in turn have implications for the structure of the Universe. Reliable observational input in cosmology to test these ideas is scarce and the ability to perform controlled experiments, of course, absent. However, such transitions exhibit many generic features which are also found in symmetry-breaking transitions in condensed-matter systems at low temperatures.



Experimental verification of the Kibble-Zurek cosmological scenario of defect formation in Helsinki experiments. Steps in the NMR signal indicate nucleation of quantized vortices after each micro Big-Bang event triggered by neutron absorption.

The analogy between symmetry-breaking phase transitions in cosmology and in condensed-matter systems suggests, first, that many of the physical phenomena conjectured to have occurred in the early Universe would have a counterpart in the laboratory, where controlled experiments can be carried out. And, second, it suggests that the symmetry-broken ground state of the present observable Universe, i.e., today's physical vacuum, would have various aspects in common with equilibrium states in condensed-matter system.

Following Zurek's suggestion, a number of experiments were carried out in the nineties, first on liquid crystals, and later also on helium-4 in Lancaster and helium-3 in Helsinki and Grenoble, aimed at measuring the densities formed in a rapid quench through the transition. The liquid crystal and helium-3 experiments produced results in remarkable agreement with the Kibble-Zurek predictions.

Gravity

In practically all condensed matter systems (even of different universality classes), the effective action for some bosonic or even fermionic modes acquires an effective Lorentzian metric. That is why gravity is the field which can be simulated most easily in condensed matter. The effective metric can be induced by flowing normal fluids, superfluids, and Bose-Einstein condensates; by elastic strains, dislocations and disclinations in crystals, etc. This can be useful for simulation of different phenomena related to the marriage of gravity and quantum theory.

Probably the most surprising condensed-matter counterpart predicted is that of a black hole. Originally proposed in 1981 by Unruh of the University of British Columbia, Vancouver in the context of a normal liquid, it is now believed that a superfluid would be a better system in which to observe it. A nonuniform superfluid flow can be set up that moves faster than the (limiting) speed of the excitations (e.g. the sound speed). It then develops an event horizon that for these excitations in many ways is the analogue of a black hole event horizon. Quasiparticles are created in a quantum process at the horizon analogous to Hawking radiation, and provide a means of detection.

The most severe problem in the marriage of gravity and quantum theory is why is the vacuum not gravitating? The estimation of the vacuum energy using the relativistic quantum field theory gives a value which is by 120 orders of magnitude higher than its upper experimental limit. This, the most striking discrepancy between theory and experiment in physics, is known as the cosmological constant problem. Quantum liquids show the possible route to the solution of this problem. They demonstrate that the effective theory is unable to predict the correct value of the vacuum energy, while an exact microscopic consideration (in other words, the trans-Planckian physics) does give the zero value for the vacuum energy without fine-tuning, if the vacuum is in complete equilibrium.

Aims and objectives

T*he aim of this programme is to exploit the analogies to simulate the cosmological and other phenomena related to the quantum vacuum using ultra-low-temperature superfluid helium and other condensed-matter systems,* such as atomic Bose condensates, superconductors, Josephson junction arrays, ferro- and antiferromagnets, spin liquids and liquid crystals, optical systems, etc. The theoretical work is directed to establish existing and reveal novel analogies, and to apply the condensed matter experience to the development of the theory of quantum fields towards the Planck scale.

Cosmology-in-the-laboratory experiments in superfluid helium require the most sophisticated apparatus, in particular state-of-the-art cryogenic equipment. European experimenters are world leaders in the field of cryogenics. Members of the Programme (Krusius at the Helsinki University of Technology and Fisher at the University of Lancaster) have won prestigious international awards for their contributions to this technology. The laboratories are now equipped and ready to carry out a wide range of studies in the field: Grenoble and Lancaster can work at temperatures as low as 100 microkelvin, while Helsinki has special facilities for studying rotating low-temperature systems. Theorists and experimenters in other fields are also playing leading roles.

The present Programme grew out of a fruitful ESF Network on *Topological Defects*, which was originally concentrated on the non-equilibrium field theory in particle physics, condensed matter and cosmology. We are planning to extend the collaboration between the three communities on a broader scale to tackle the new research objectives outlined here.

The Programme

1. Testing theories of defect formation

'Cosmology-in-the-laboratory' experiments aimed at testing theories of defect formation were first proposed in 1985 by Zurek at the Los Alamos National Laboratory. He suggested studying defect formation in condensed-matter systems undergoing a symmetry-breaking phase transition as an analogue for the cosmological phase transition scenario put forward in 1976 by Kibble at Imperial College, London. If a system is quenched through the phase transition fast enough, topological defects can be created due to the evolution of uncorrelated regions of the newly formed phase. The defects appear when these regions, having different values of the order parameter, come together.

Given the universal nature of symmetry-breaking phase transitions, the premise is that if we can successfully predict defect densities in a controlled environment, the same theoretical framework can be used to predict cosmological defect densities.

Following Zurek's suggestion, a number of experiments were carried out in the nineties, first on liquid crystals, and later also on helium-4 and helium-3, aimed at measuring the densities formed in a rapid quench through the transition. The liquid crystal and helium-3 experiments produced results in remarkable agreement with the Kibble-Zurek predictions. While also the initial helium-4 experiment carried out at Lancaster University in 1994 showed agreement, an improved version of that experiment in 1998 by the same group showed no evidence of vortex formation. This is known as the helium-4 puzzle. Similar experiments with superconducting films at the Technion in Haifa have also failed to show such evidence.

It is clearly important to resolve this confusion. Recently theorists at Imperial College, London, proposed an explanation based on a thermal field theory analysis, focusing on the effect of short wavelength thermal fluctuations, but more needs to be done both experimentally and theoretically to establish whether this explanation is correct.

- Groups in Salerno, Paris VI and Los Alamos are working on theoretical descriptions of defect formation during a rapid phase transition based on the full microscopic quantum dynamics rather than the effective theories of the Ginzburg-Landau type that have been used so far. A key question, to which we have as yet only a very partial answer, is how the quantum dynamics of the microscopic theory generates the macroscopic time scale of the formation process.

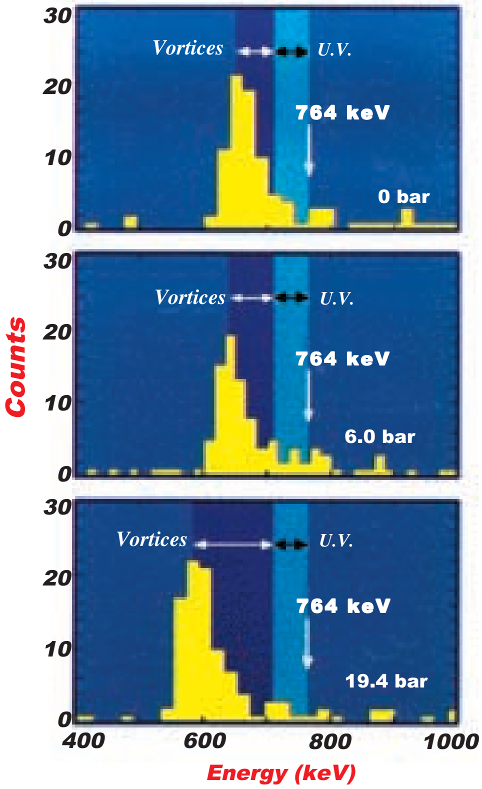
- On the experimental side, the Lancaster group is planning a further improved version of their helium-4 experiment with substantially improved sensitivity. They should see vortices even if the actual defect density is two or three orders of magnitude below the Zurek prediction.

- To further test our ideas, we also plan to investigate Josephson junction arrays, liquid crystals, and the so-called photon fluids. This is a new state of light which exists in a Fabry-Perot cavity filled with an atomic gas. In such a nonlinear cavity, the photons acquire a mass and a self-interaction. The resulting theory closely resembles that of a superfluid, with the great advantage that the strength of the photon-photon interaction can be changed by detuning the frequency of an external laser. Unlike in a superfluid, this permits an easy realisation of a variety of experimental situations, and is therefore ideally suited to test our ideas.

- Experiments on liquid crystals will be carried out at the University of Maribor, Slovenia. As in superfluid helium-3, there exists a variety of liquid-crystal phases with different spontaneously broken symmetries. Because of the liquid nature of these phases, equilibrium is usually achieved on experimentally accessible time scales, and a host of ‘cosmology-in-the-laboratory’ phenomena can be studied. The Maribor group plans to study defect formation, evolution and annihilation. Parallel theoretical studies will be undertaken in Maribor and Krakow.

2. Inhomogeneous vacuum and phase transitions in systems with gauge fields

- Condensed matter simulations demonstrate that the inhomogeneity of the system is an important factor in the process of defect formation, so that the Kibble-Zurek scenario must be modified to include this factor. This issue has been addressed by several theoretical groups: at the Jagellonian University, Krakow in collaboration with the group in Los Alamos, and in Helsinki University of Technology in collaboration with Argonne National Laboratory. The novel condensed matter systems, where the effect of the inhomogeneity can be studied in controlable way consists of an extremely porous material (aerogel)



Complementary experiments to that in the previous Figure. In Grenoble and Lancaster the neutron absorption event is monitored by a quasiparticle detector. The energy deficit is attributed to vortices, which are invisible to the detector.

immersed in superfluid helium-3. The CNRS-CRTBT Group at Grenoble plans to investigate this system.

- There is a possibility that new exotic states of superfluid helium-3 with partially disordered order parameter can exist in such a material as aerogel. The ground state of new phases of superfluid helium-3 can be considered as distributed topological defects – strings, walls, monopoles, solitons. Random anisotropy of strands in aerogel, which according to the Imry-Ma scenario destroys partially or completely the long-range order, plays the same role as thermal fluctuations in gauge theories, and especially in gauge systems with nonabelian symmetries, where the pattern of symmetry breaking is often complicated and still is not well known. In such systems with the marginal order the topological defects of various types become the main factor which determines the nature of the symmetry breaking. The parallel study of the marginal order in condensed matter and in relativistic gauge theories may shed light on the problem whether the electroweak symmetry breaking occurs via a true phase transition or as a continuous crossover.

● In particular, we aim to develop a dual description of the dynamics of phase transitions involving gauge fields, and to carry out numerical simulations using this approach. Monte Carlo simulations carried out in 1999 at the Norwegian University of Science and Technology, Trondheim, convincingly demonstrated the validity of this approach.
There is considerable expertise with this approach among theorists at the Free University Berlin and Imperial College, London.

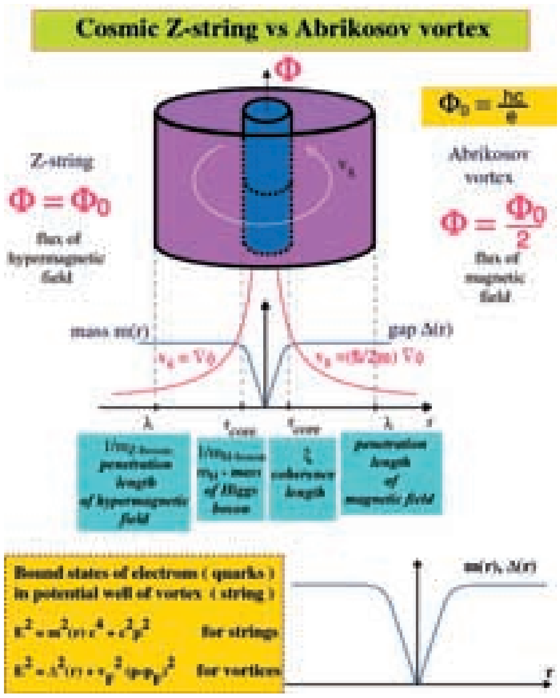
● The formation of topological defects in such transitions is much less well understood than in systems without gauge fields. Numerical simulations on two-dimensional systems at Los Alamos and in three dimensions at the University of Sussex seem to be in agreement with the standard Kibble-Zurek scenario. The best condensed-matter counterpart for simulation, both experimentally and theoretically, is the normal-to-superconducting transition in superconductors with local and semilocal symmetry groups.

3. Exotic defects

The nature and properties of topological defects formed at a symmetry breaking phase transition often contain important information about the symmetries that were broken during the transition. In systems with nonabelian symmetries, the pattern of symmetry breaking is often complicated, leading to the appearance of several different phases and many exotic types of defects. Given the ubiquity of these transitions, the study of exotic defects in low-temperature systems can provide valuable clues for the early universe.

● ***Half-quantum vortices and walls terminating on strings***

We are planning an experiment to observe for the first time half-quantum vortices in ^{3}He-A. These vortices with fractional circulation number are the condensed-matter counterparts of so-called Alice strings, which are predicted by some cosmological models. Alice strings have the remarkable property that a charged particle circling the string once flips the sign of its charge. Their ^{3}He-A counterparts, the half-quantum vortices, have the property that a quasiparticle winding around the vortex once flips its spin. This surprising behaviour is rooted in the non-Abelian character of the helium-3 symmetry.



Cosmic string and Abrikosov vortex have the same structure. Both have two cores: the inner core characterizes the distribution of the order parameter (the Higgs field), while in the outer core the (hyper)magnetic field is concentrated. Due to bound states of fermions and quasiparticles in the inner core, the dynamics of string leads to baryogenesis, while the dynamics of vortices leads to momentogenesis measured in Manchester experiments.

The important property of the half-quantum vortex in ^{3}He-A and in other condensed matter systems, e.g. in superconductors, is that the Alice string serves as the termination line of a topological wall, such as a soliton or grain boundary. It is thus the counterpart of the wall terminating on a string which can appear in quantum field theory if a sequence of broken symmetry phase transitions takes place. Another condensed-matter example of such a combined defect – the spin-mass vortex with soliton tail – has been recently observed to be created in a rapid quench in rotating ^{3}He-B caused by neutron irradiation. This provided an independent evidence for the Kibble-Zurek scenario. The related combined defects – strings terminating on monopoles – can be also reproduced in ^{3}He and unconventional superconductors.

Experimentally, a half-quantum vortex can be created by putting a wire in the centre of a cylindrical cell containing normal helium-3 liquid and cooling it down to the A phase while uniformly rotating it. The central post acts as a pinning centre for a half-quantum vortex, which can be detected by looking for a characteristic peak in the NMR absorption spectrum coming from the soliton emanating from the Alice string.

● ***Defects across a phase boundary***

Given the sequence of symmetry-breaking phase transitions believed to have taken place in the early Universe, an important question for cosmology is the fate of topological defects crossing a phase boundary or suffering a subsequent phase transition. In general, the defect may be very different on opposite sides of the transition and nontrivial readjustments are required. In some cases, such changes have a tremendous impact on cosmology. One noteworthy example is the class of processes by which monopoles created in one phase transition become connected by strings in a subsequent phase transition. The strings enhance the annihilation rate of the monopoles, thus eliminating the over-abundance problem altogether. A similar mechanism is involved in some models of baryogenesis.

In superfluid helium-3, two different phases – the A phase and B phase – can be present simultaneously in a single container, separated by an interface. At a low enough temperature, the container can be put in rotation, while the nucleation of vortices is monitored in both phases separately. It is expected that initially vortex lines will form exclusively in the A phase and only later will the vorticity be transferred to the B phase via some mechanism at the A-B interface. Previous experiments carried out in 1993 in Helsinki on moving A-B interfaces indicated that for slowly moving interfaces, the A-phase vortices were pushed away in front of the phase boundary, and that penetration of the interface took place only for faster moving boundaries. By locking the interface, we expect to be able to study the mechanism in detail, and thus to obtain important clues as to how topological defects are transplanted into a new phase. The experiment is now being performed in Helsinki University of Technology.

Analogous phenomena may have occurred in the early Universe, because certain models for example a grand unified model based on the group SU(5) predict metastable vacuum states in addition to the stable one. Thus these experiments may have interesting cosmological implications.

● ***Q-balls***

Q-balls are time-dependent soliton-like states of non-topological origin. These coherent states are long-lived with their frequency and stability determined by the conservation of a global charge, say the baryonic charge in cosmology, or the spin projection on the direction of an applied magnetic field in condensed matter. As for topological defects, the ground state inside a Q-ball can be different from that outside the lump. Q-ball nucleation and subsequent growth might play a role in first-order phase transitions such as the A-B transition is superfluid helium-3. In the context of cosmology they could contribute to dark matter.

The so-called Homogeneously Precessing Domain (HPD) first discovered in 1989 and recently studied at Grenoble in the superfluid ^{3}He-B phase can be understood as a Q-ball for which the global charge is the total nuclear spin of ^{3}He atoms. Because of their importance to cosmology, in parallel with the ongoing experimental work in Grenoble, theorists at the Universities of Crete and Athens plan to investigate the dynamics of these magnetic Q-balls, including the loss of their stability due to the creation of quasiparticles from the vacuum.

● ***Zero modes in defect cores***

The energy spectrum of fermions bound to a vortex core can cross zero as a function of linear or angular momentum. Fermionic zero modes determine the dynamics of vortices in superfluids and superconductors. They also play a role in stabilizing closed cosmic strings, so-called vortons.

In superfluid ^{3}He-B there is the possibility to directly observe fermionic zero modes in non-axisymmetric vortices using an HPD. In the core of these vortices, the axisymmetry is spontaneously broken. This is similar to the breaking of the electromagnetic symmetry in the core of cosmic strings known as superconducting strings. The fermionic zero modes are predicted to manifest themselves through resonances when the external frequency is a multiple of the level spacing of the energy spectrum in the core.

4. Analogues of gravity

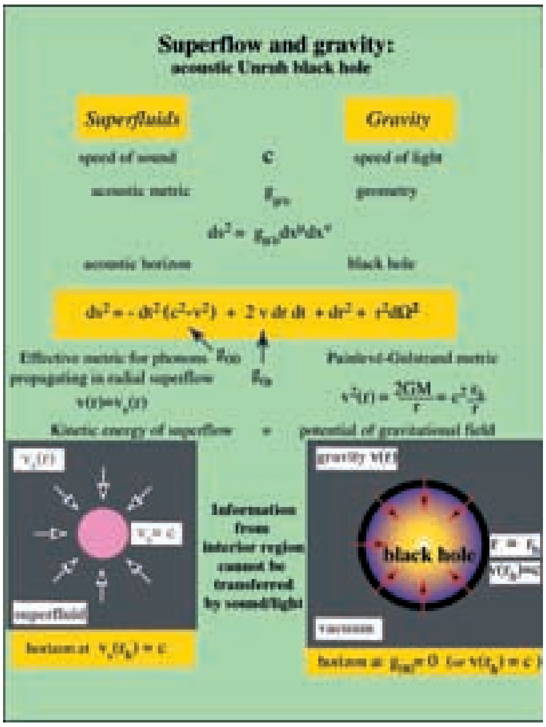
The condensed matter analogue of gravity allows us to simulate different types of exotic metric and investigate the behaviour of the quantum vacuum and bosonic and fermionic quasiparticles in nontrivial curved space-time.

● ***Spinning cosmic strings***

At the moment only one of the exotic metrics has been experimentally simulated. This is the metric induced by a spinning cosmic string, reproduced by a quantized vortex in superfluids and superconductors. The spinning string gives rise to the analogue of the gravitational Aharonov-Bohm effect, experienced by (quasi)particles in the presence of such a string. This type of Aharonov-Bohm effect has been experimentally confirmed in superfluid helium-3 by measurement of the Iordanskii force acting on quantized vortices.

● ***Black holes***

As a long-term goal, we plan to realise and study the analogues of black holes in different condensed matter systems at ultra-low temperatures. The most



The motion of superfluid or Bose condensate produces an effective Lorentzian metric for quasiparticles. This motion can be arranged to form an event horizon for quasiparticles. This will allow us to simulate the effect of Hawking radiation and investigate the properties of the quantum vacuum in strong gravitational field.

promising candidates are an atomic Bose condensate, a film of superfluid helium-4, and a thin film of ^{3}He-A flowing on a substrate of superfluid helium-4. The technological and engineering aspects of this experiment are extremely challenging because of the required sensitivity and the ultra-low temperatures. But detailed analysis has shown that the experiment is within the reach of our low-temperature laboratories, and is doable within the next 4 to 5 years. The theoretical work is aimed to develop the black hole theory by incorporation of the Planck energy scale using the condensed matter experience with 'acoustic' black holes, where the microscopic 'trans-Planckian' physics is instrumental. In particular, the problem of stability of the quantum vacuum in the presence of the horizon will be studied in parallel in superfluids and for 'real' black holes.

- ***Cosmology***

There are other open questions in cosmology which can be studied in parallel with condensed matter: vacuum energy, quintessence, inflation, growth of quantum fluctuations, decoherence, etc.

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Workshops and conferences

To explore the research frontiers and to evaluate the progress, workshops or conferences will be held every year.

- Inaugural workshop on *Cosmology in the Laboratory,* Imperial College, London, United Kingdom, 7-10 July 2001. Web site: *http://theory.ic.ac.uk/coslab.html*

- Summer school, Cracow, Poland, 15-29 September 2002.

- We also expect to mount joint conferences with related ESF activities.

Short scientific visit grants

For travel grants see our web site: *http://www.esf.org/coslab*

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