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Cosmology: The shards of broken symmetry

[NEWS AND VIEWS]

Zurek, Wojciech H.

Wojciech H. Zurek is in the Theoretical Astrophysics Group, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA.

A COSMOLOGICAL experiment sounds like an impossibility. Yet precisely such a feat is described in two complementary papers in this issue. Two groups, one based in Grenoble [1] (page 332), the other in Helsinki [2] (page 334), report on a pair of superfluid helium-3 experiments, devised to probe the dynamics of the cosmological phase transitions that are thought to have occurred a fraction of a second after the Big Bang.

As the Universe expanded and cooled, the fields that mediate fundamental forces (believed to be unified at a very high temperature) underwent a sequence of symmetry-breaking phase transformations. The effect was to select the particular broken-symmetry vacuum of the Universe we inhabit, with its gravitational, electromagnetic, weak and strong interactions, and their associated entourages of elementary particles. As Tom Kibble pointed out [3], phase transitions can lead to topological defects (monopoles, cosmic strings or domain walls) which can have either desirable or devastating consequences for different cosmological theories.

Spontaneous symmetry breaking is familiar in the context of condensed matter. A ferromagnet cooled below the critical temperature is the classic example. As thermal fluctuations decrease, it becomes energetically favourable for different elementary magnets to point in the same direction, selected at random; the choice of direction breaks the spherical symmetry that the ferromagnet has above the critical point. But theories that govern phase transitions in cosmology and in condensed-matter physics are essentially identical, so experiments on cosmology can in theory be performed in a laboratory.

Common to cosmology and condensed-matter physics is the question, how big are the pieces of broken-symmetry vacuum just after the phase transition? The size of such coherent domains manifests itself in the initial density of topological defects. These are intrusions of the old symmetric vacuum, imprisoned by configurations of the new broken-symmetry state that are impossible to disentangle. For example, when symmetry breaking involves two distinct choices, at a boundary between the two such regions there will be a domain wall (Figure 1). One can expect approximately one 'unit' of topological defect -- one monopole, a domain-sized piece of a string, or a 'tile' of a domain wall -- per domain [3], so the initial density of defects gives the size of the pieces of broken symmetry.

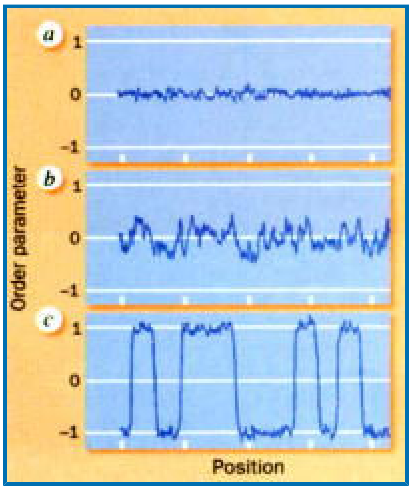

Figure 1. Numerical simulation of the formation of topological defects (known as 'kinks' in this one-dimensional case) during a phase transitional [10]. a, The order parameter psi at high temperature oscillates around zero. b, As the transition gradually takes place, psi must choose between +1 and -1. c, When domains with different values of psi meet, a kink connects them.

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Superfluids are an excellent example of symmetry breaking that leads to topological defects. They are described by a complex 'order parameter', psi = [vertical bar] psi [vertical bar] e^{i} theta, a wave function of the Bose condensate of helium atoms. In some ways, psi can be thought of simply as a probability wave familiar from ordinary quantum mechanics. The square of its absolute value gives the density of the superfluid, which in a sense is the probability of finding an atom of superfluid at a particular point. But the analogy is incomplete. The wavefunction of the superfluid Bose condensate does not satisfy the superposition principle, and its square is not conserved. Moreover, in helium-3 the order parameter psi is not just a complex number, but a tensor, which describes rotational states of the pairs of sup 3 Helium atoms (individual^{3} Helium atoms are fermions, and like electrons in a superconductor they must pair before they can Bose-condense).

Symmetry breaking is induced by a change in the shape of the effective potential. Above the critical temperature, the potential minimum is at the origin and psi fluctuates near there (Figure 2), but below the critical point the potential has a minimum away from the origin, along a rim of the 'sombrero'. To settle there, psi has to break symmetry -- it has to choose a value of theta.

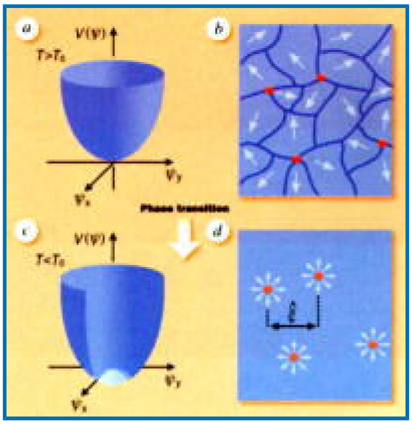

Figure 2. Dynamics of defect formation in superfluids. a, b, Above the phase transition, the two-dimensional (complex) order parameter psi fluctuates around the minimum of the potential, assuming values which point in approximately the same direction (or phase, theta) within each local domain. c, d, When this configuration is frozen out by the phase transition, the symmetric phase will be trapped in some locations: these are defects. In superfluids, such defects are lines of vortical flow. Their energy is related to the difference in potential energies between the hill at psi = 0 and the minimum along the circle of broken-symmetry configurations. It can also be regarded as the energy of rotation of the vortex.

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Topological defects in superfluids arise when the phase, theta, changes continuously by 2 pi along a closed path in space -- then there must be a point inside the loop where pi theta undefined. The arrows representing the order parameter will all be pointing either directly towards or away from the 'vortex line', where the field is forced to climb back on top of the sombrero to assume the only value, psi = 0, that does not require making a choice of phase. A gradient in theta necessarily implies a flow, just as an ordinary plane wave flows in the direction of changing phase. In this case the flow pattern is a vortex of superfluid with a non-superfluid core.

The energy corresponding to this rotation was used by the Grenoble group [1] to defect the presence of vortex lines -- superfluid analogues of cosmic strings. This can be done by heating up a small volume of superfluid^3 Helium and letting it cool down rapidly, so for a short while the system is in a non-superfluid state. When it returns below the critical temperature, different pieces independently choose the manner in which their symmetry is spontaneously broken. The initial energy used to heat up the fragment of the superfluid above the critical temperature is precisely known, so by monitoring the energy that escapes, one can find out how much of it remains in the vortex lines. The Helsinki group uses an identical procedure to generate defects [2], but they do it at a somewhat higher temperature, and they use a technique that allows them to count the loops of string-like vortex lines one by one. In both experiments the initial density of vortex lines is found and used to infer the average size of the like-minded pieces of newly made broken-symmetry superfluid.

The answer confirms a theory of the initial domain size based on a combination of causality and equilibrium thermodynamics [4] (see box). A rough confirmation of these ideas from^4 Helium experiments was already at hand [5], but^4 Helium has a very different set of experimental parameters, which allow for generation of a much more plentiful vortex tangle but which also make the subsequent determination of their density more difficult. Thus, it was only possible to set a lower limit on the initial density of vortex lines.

The three experiments [1,2,5] together confirm the simple ideas outlined in the box [3,4,6], and open up a new area of inquiry: the non-equilibrium aspects of phase transformations. Their implications go beyond the issue of topological defects. For instance, it may be possible to restore the chiral symmetry (corresponding to the quark-hadron transition) of a nucleus-sized piece of the Universe in accelerator experiments in the near future [7]. We could then see chiral symmetry breaking of the vacuum, resembling phenomena in the heated bubble of^3 Helium. The analogy is not complete -- in this case the sombrero potential is tipped and there is no possibility of defects, but this was one of the last transitions to occur as the Universe cooled. Moreover, the size of the pieces of the broken-symmetry chiral vacuum can translate into measurable fluctuations in the number of pions.

The experimental confirmation of the mechanism for defect formation alone does not determine whether they exist in our Universe; for that, one needs to know more about the Grand Unified Theory and its relationship to the present-day low-temperature vacuum [8,9] -- it is the topology of the broken-symmetry vacua that decides whether the order parameter can disentangle itself, or whether it has to leave behind traces of discord, crystallized out as, say, cosmic strings. But we can now be confident that when defects are possible in principle, they will appear with an initial density that can be predicted by a theory now tried and tested in superfluids.

Wojciech H. Zurek is in the Theoretical Astrophysics Group, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA.

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