Relic topological defects from brane annihilation simulated in superfluid ^{3}He

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Although it is widely accepted that to resolve the 'horizon' problem the early Universe must have undergone a sudden expansion (cosmic inflation), what mechanism drove this process is less clear. In the braneworld scenario, it is suggested that inflationary epochs may have been initiated and terminated by brane collisions and annihilations[1–3]. Branes are objects of lower dimensionality embedded in a higher-dimensional matrix. For example, we may live on a three-dimensional brane embedded in a four-dimensional matrix. However, such structures are so far removed from everyday reality that bringing physical insight to bear is difficult. Here we report laboratory experiments where we simulate brane annihilation using the closest brane analogue to which we have access, the coherent phase boundary between the two phases of superfluid ^{3}He. When two branes collide or annihilate, topological defects may be created, whose influence may still be detectable today. By creating a brane–antibrane pair in superfluid ^{3}He and subsequently annihilating it, we can detect that defects are indeed created in the superfluid texture (the superfluid analogue of spacetime), thus confirming that the concept of defect formation after brane annihilation in the early Universe can be reproduced in analogous systems in the laboratory.

Among several candidates for providing the trigger for inflation, one attracting current interest is the braneworld scenario. Branes, created during symmetry-breaking phase transitions in the early Universe, are lower-dimensional structures embedded in a higher-dimensional matrix. Our present Universe may be confined to a brane, making us unaware of the surrounding higher-dimensional space. Brane collision and annihilation may be responsible for initiating and ending periods of inflation[1–3].

The various transitions undergone by the Universe after the Big Bang left the broken symmetries $SU(3) \times SU(2) \times U(1)$. The closest analogue system to which we have current experimental access is superfluid ^{3}He in the zero-temperature limit. The superfluid ^{3}He condensate, similar to the condensate in a superconductor, is made up of Cooper pairs, but here pairs of ^{3}He atoms, which, being extended particles, favour *p*-wave pairing, where the pair orbital momentum L is unity (ensuring the zero probability of finding the two members of the pair in the same position). Because L is odd, symmetry requires the nuclear spins to couple symmetrically and thus the pair spin angular momentum S must also be unity. The condensate order parameter must define both the directions of the Cooper pair angular momentum vector $\mathbf{l}$ and spin vector $\mathbf{s}$ and also a phase, thus breaking $SO(3) \times SO(3) \times U(1)$

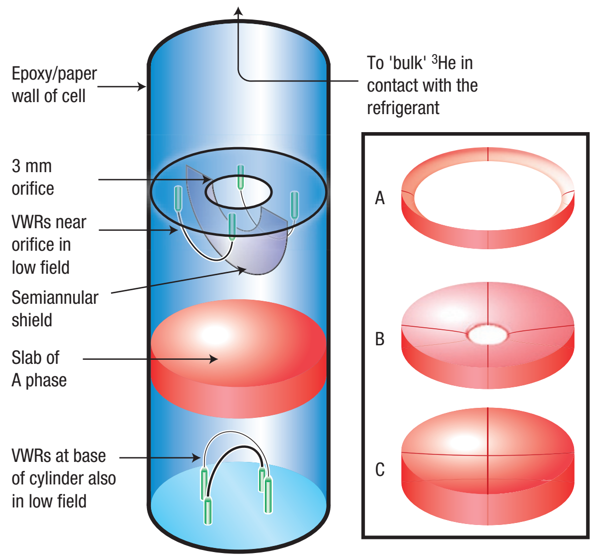

Figure 1 The experiment. The cylinder containing the superfluid ^{3}He is 8 mm in diameter with an active length of 45 mm. A 3-mm-diameter orifice at the top connects the liquid in the cylinder to the bulk superfluid outside, which is cooled by nuclear adiabatic demagnetization of copper to 150 μK. Two vibrating-wire resonators (VWRs) are placed in the liquid at the top and bottom of the cylinder in low magnetic field. The very small damping force on these resonators yields the quasiparticle excitation density, from which we can infer the temperature. When driven at higher velocity, the resonators can break Cooper pairs, thus creating more excitations (in other words heating the superfluid) in a controlled way. The two upper resonators are mutually shielded from any ballistic excitations generated by the other by a semiannular shield. The field profile can be adjusted to create a slab of A phase across the cylinder as shown. Inset: to check that defects detected indeed arise from the annihilation of the two phase-boundary 'branes' we can adjust the shape of the A-phase volume, as the field is increased, from an annular ring (A) (which with decreasing field disappears from the cylinder gradually with no annihilation process) to a complete slab filling the whole cell cross-section C (which does involve an annihilation on removal).

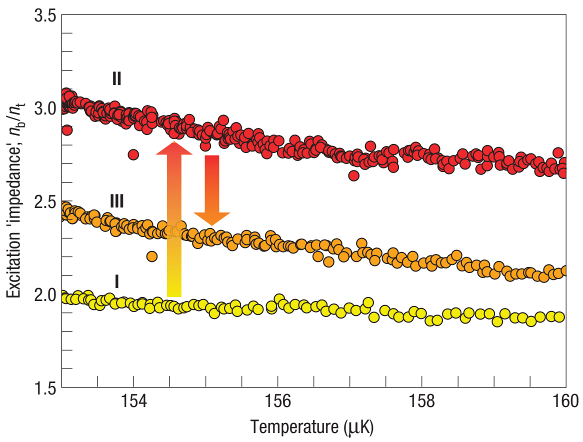

Figure 2 The measured impedance. The measured ratio n_b/n_t as the cell warms from 150 to 160 μK over a period of several hours. Data I correspond to the virgin configuration before introduction of the A-phase slab, II to that with the A-phase slab and III to the final configuration after A–B/$\overline{\text{B–A}}$ annihilation. In practice, each dataset has to be taken in a separate cool-down, and the three datasets shown in the figure represent more than a month's worth of data-taking. Configurations I and II are reproducible from cool-down to cool-down and yield the same impedance. However, after annihilation, the state is not reproducible and thus datasets III show variation well above the experimental scatter.

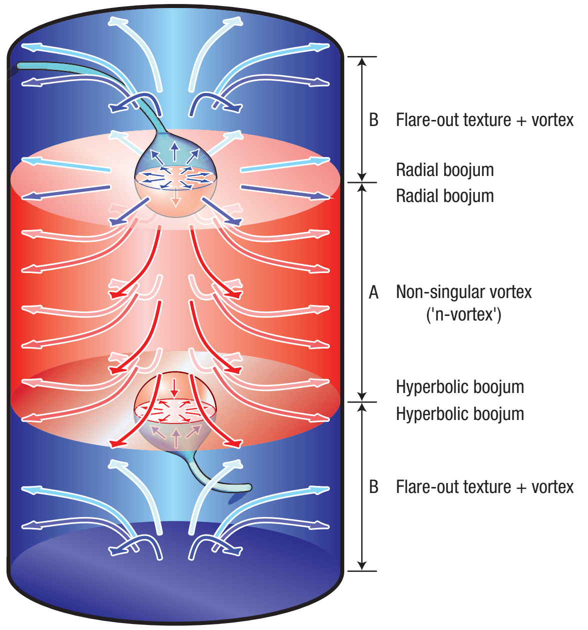

Figure 3 The textures before annihilation. The arrows indicate the direction of the **l** vector, which is constrained to intersect the cylinder boundary perpendicularly and to lie parallel to the phase interfaces. We assume the B phase (blue) will preserve the 'flare-out' texture it had before the A-phase (red) slab was introduced. The simplest A-phase texture is shown. To accommodate this there must be two zero-dimensional defects on the axis (boojums), a 'source' radial boojum on the upper A–B interface and a hyperbolic boojum on the lower interface, providing a sink for vertical **l** and a source for horizontal **l**. The two boojums must be connected by a non-singular vortex. (We have ignored the fact that the **l** vectors on the two sides of the interfaces must lie perpendicular to each other, which simply adds a twist to the pattern.) The non-singular vortex, being associated with a quantum of circulation, cannot terminate at the interface but must continue into the B phase as a hard-core vortex terminating on the cell boundary, with the boojum extending into the B-phase side to provide the matching across the interface.

symmetry[4]. This structure clearly shares many of the properties of the broken symmetries of the Universe. It is also sufficiently complex that the superfluid may exist in several phases, the two most stable being the A phase and the B phase. Under the zero-pressure and low-temperature conditions of our experiments, the B phase is stable up to a magnetic field of 340 mT, which induces a transition to the A phase. Thus, by applying a field gradient, we can stabilize and manipulate an A–B interface[5]. Because the order parameter transforms continuously between the two phases, the interface is itself coherent and represents the most coherent two-dimensional structure we know of. This is our analogue cosmological 2-brane in the three-dimensional bulk matrix. The precise correspondence between the ^{3}He phase interface and a cosmological brane is still a matter of discussion, the closest correspondence probably being to the D-brane. For the present purposes we may note that the correspondences are as much topological as specific.

Braneworld scenarios associated with the inflationary epoch tell us that the symmetry lost in brane–antibrane annihilation may lead to the production of strings, defects of lower dimension[6]. If we can produce and annihilate an analogous brane–antibrane pair, and then find relic topological defects in the resulting single phase, that would provide strong laboratory support for such scenarios[3]. Using a profiled magnetic field we can bisect the B-phase background with a slab of A phase, creating an A–B and a $\overline{\text{B–A}}$ interface, our brane and antibrane. Decreasing the field thins the A-phase slab, bringing the A–B/$\overline{\text{B–A}}$ interfaces closer and finally forcing them into a simulated brane–antibrane annihilation. Subsequently, we examine the remaining bulk B phase for evidence of defect production.

Here we are able to take advantage of the superfluid's own unique properties. The broken symmetries of the condensate, ensuring a global direction for the **l** and **s** vectors, give the liquid a real physical directional structure, the 'texture', much like (but more complex than) the texture in a liquid crystal. In a magnetic field the superfluid energy gap in the B phase depends on the direction relative to the **l** vector, such that the broken-symmetry structure of the liquid is actually reflected in the structure of the gap. At the very lowest temperatures, we still have a few unpaired ^{3}He atoms, which form quasiparticle excitations above the gap. Thus a quasiparticle moving through the condensate experiences a local potential that depends on the local texture. Therefore, by measuring the impedance experienced by a flux of such excitations we can infer the existence of any defects spawned by the annihilation[6].

The experiment, shown in Fig. 1, is carried out at ∼150 μK in a vertical cylinder of superfluid. At the top and bottom of the cylinder are mounted pairs of vibrating-wire resonators, which act as excitation generators and detectors[7]. The experiment is surrounded by a complex set of superconducting solenoids to provide the field profile necessary to create and manipulate the phase-interface branes.

We excite the lower heater resonator to generate a flow of excitations up the cylinder, and measure the increase in quasiparticle density at the top (n_t) and bottom (n_b) of the cell with the thermometer resonators. A gradient in quasiparticle density implies resistance to quasiparticle transport from bottom to top, and increases the ratio, n_b/n_t. We use this ratio as a measure of the effective quasiparticle 'impedance'.

To infer the response of the system to the brane annihilation, we make three measurements: I, we measure the impedance when the cylinder is filled with B phase in a field just below that

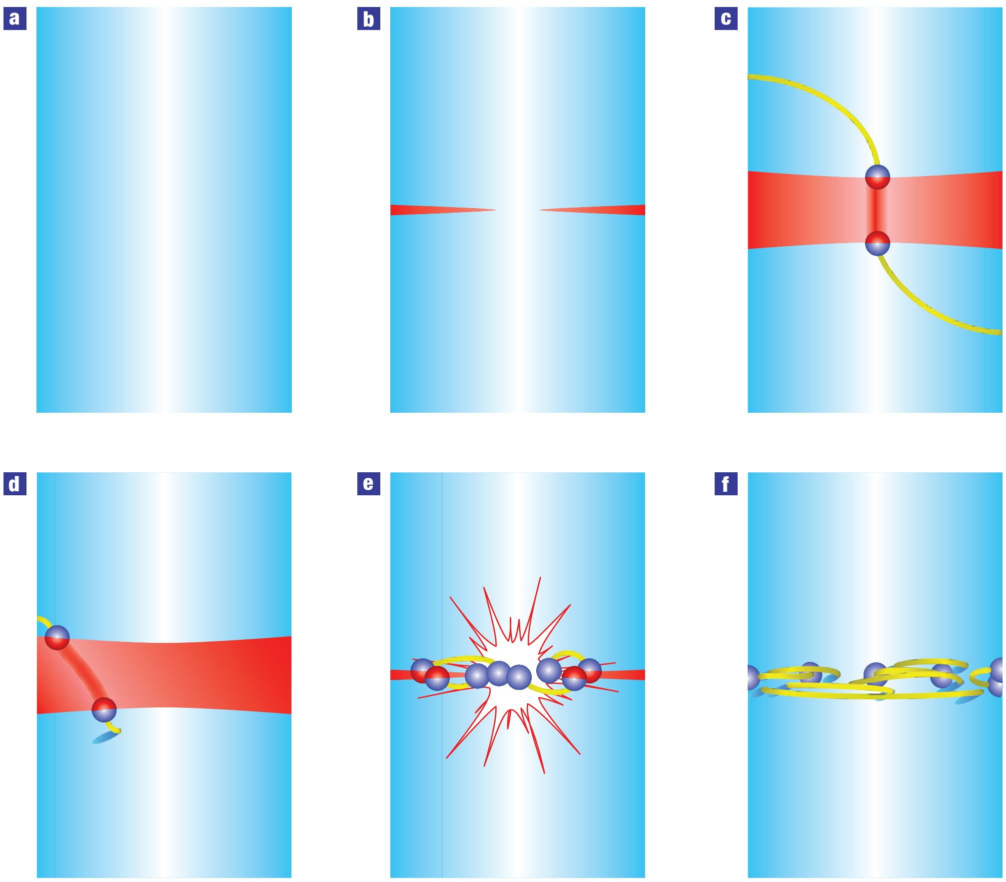

Figure 4 The complete defect-formation process. A speculative cartoon. **a**, The initial state with B phase (blue) filling the cylinder. **b**, A phase (red) is introduced. **c**, An A-phase slab crosses the cylinder. At least two boojums (see text and Fig. 3) must appear to satisfy the textural constraints, along with a non-singular vortex across the slab, which continues as a vortex in the two B-phase volumes (yellow). **d**, This symmetrical picture will in practice be distorted by the line tension in the vortices and the boojums pulled to the walls. **e**, The field is rapidly reduced and the two interfaces annihilated. Violent motion of the interfaces (see text) will generate many more defects. **f**, Equilibrium is regained with many boojums at the walls connected by line defects creating a tangle, partially blocking the cross-section of the cylinder.

needed to produce an A-phase slab; II, we increase the field by the small amount needed to stabilize the A-phase slab, thus creating an A–B and a $\overline{\text{B–A}}$ brane crossing the cylinder, and remeasure the impedance; III, we return the field to its starting value, annihilating the brane–antibrane pair as the A-phase slab disappears, and measure the impedance once more. The question posed by the experiment is simply this: does the brane annihilation return the liquid to its initial 'virgin' state or to some other state containing defects?

Figure 2 shows a section of the measured impedances for configurations I–III as the cell slowly warms. It is clear that the impedance is higher after the A-phase slab has been introduced and subsequently annihilated. This means that textural defects impeding the quasiparticle transmission must be left in the texture after the annihilation of the A–B and $\overline{\text{B–A}}$ interfaces. Further, these defects form only after an annihilation process. If we adjust the field profile to create only a partial A-phase block across the cell (Fig. 1, inset), then subsequent removal of this A phase is gradual (that is, no annihilation), and the impedance does not change from its configuration I value.

To understand the defect creation process we consider first the texture before annihilation. For simplicity, we concentrate on the textures defined by the spatially varying directions of the orbital vector **l**. In both phases, the solid-wall boundary condition forces the **l** vector to impinge perpendicularly on the cylinder walls. In the B phase this conflicts with the weaker tendency of the external magnetic field to orient the B-phase **l** vector parallel to the field direction. These two effects ensure that in a long cylinder the B phase (configuration I) takes up the well-known 'flare-out' texture[8], with an axial **l** vector bending at the walls.

What would happen if a slab of A phase were now introduced (as shown inset in Fig. 1) across the existing B-phase texture?

At an A–B phase boundary the **l** vectors are additionally constrained to lie in the boundary plane and perpendicular to each other. As long as the A-phase slab is not fully formed, for example during stages A and B of Fig. 1, the **l** textures in both phases can comply with the constraints by continuous deformations (except where the phase boundaries meet the walls). However, once the A-phase slab is complete, two point singularities (one with radial and one with hyperbolic **l** distributions) must appear on the A–B and B–A interfaces. In the A phase, these two point singularities are connected by a non-singular line defect in the **l** field. Because this defect carries one quantum of circulation, it cannot terminate on the interface, but must continue into the surrounding B-phase regions as a vortex terminating on the container wall (G. E. Volovik, private communication). This pattern is shown in Fig. 3.

The symmetric arrangement of Fig. 3 would be short lived, because the tension of the B-phase vortices would pull the point singularities to the wall along the two interfaces, leaving two surface point defects, connected by the non-singular A-phase vortex. We could also imagine more complex arrangements with multiple defects existing simultaneously. Either way, this structure is already reminiscent of the pattern of a brane–antibrane pair linked by linear defects which appears in some braneworld scenarios; see, for example, refs 6,9.

We now consider what defects the annihilation process might produce that would be capable of generating the observed quasiparticle impedance. It is unlikely that the observations are due to a simple planar defect stretching across the cylinder. The B phase can support such topologically stable objects ('n solitons'[10]) in the presence of a magnetic field. However, simply from energy considerations such a soliton would be expelled from the high-field annihilation region unless strongly pinned at the walls. Also, given the violence of the annihilation process, it is difficult to believe that such a uniform defect could ever be created. Finally, our observed impedance, which varies with each annihilation, is not compatible with a reproducible soliton defect. We must therefore expect zero- and one-dimensional defects.

As the two interfaces approach each other with falling field, the first breakthrough takes place on the axis of the cell (see Fig. 1, inset). This will generate extremely high local accelerations of the phase boundary, as surface tension pulls apart the sharp edges around the initial breakthrough. This is likely to be violent, creating oscillations in the phase boundary and possibly resulting in droplets of A phase separating from the thinning slab. Under such conditions, we may reasonably expect that large numbers of both point and line defects would be formed.

Zero-dimensional defects created in this way would have to end up on the cell walls, whereas the line defects would form a tangle across the high-field region of the cylindrical cell pinned at the walls. These line defects represent a local reflecting potential for the quasiparticle flux. The irreproducible tangle of such defects created on each annihilation would provide the variation in impedance III that we observe. From the distortion of the B-phase gap by a linear defect we can estimate that the impedance we measure after annihilation is compatible with of the order of 10^2 such defects crossing the cylinder being created during the annihilation process, which is by no means unreasonable. This scenario is illustrated in Fig. 4. We should emphasize that this picture is speculative. Although we definitely see defects created during annihilation, identifying exactly what they are is no easy matter and awaits further investigation.

We can draw three conclusions. First, the interface separating the A and B phases in the highly coherent matrix of superfluid ^{3}He at temperature $T \sim 0$ provides the best analogue brane we currently have. Second, the annihilation of two such branes, an A–B and a $\overline{\text{B–A}}$ interface, generates topological defects in the background textural metric. Third, this confirms that the concept of defect formation associated with brane annihilation in the early Universe can be reproduced in analogous systems in the laboratory.

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