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A Cosmological Experiment in Liquid Helium

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ALTHOUGH the birth of the universe is inaccessible to human experimental investigation, aspects of cosmological theories can nonetheless be explored in the laboratory. Tiny inhomogeneities in the mix of particles and radiation produced in the Big Bang grew into the clusters of galaxies that we see today, but how those inhomogeneities arose and grew is still unclear. Cosmologies based on grand unified theories suggest that a symmetry-breaking phase transition occurred via the Higgs mechanism about 10^{-34}s after the Big Bang as the Universe cooled through a critical temperature of 10^{27}K. It has been proposed by Kibble[1] that this transition may have generated defects in the geometry of space-time (such as cosmic strings), which provided the inhomogeneities on which galaxies subsequently condensed. Zurek[2−4] has suggested that it might be possible to model this cosmological phase transition by a laboratory analogue, the superfluid transition of liquid ^{4}He induced by fast adiabatic expansion through the critical density. Here we report the results of such an experiment. We observe copious production of quantized vortices[5], the superfluid analogue of cosmic strings. These results support Kibble's contention that such defects were available in the early Universe to seed galaxy formation.

The analogy[2−4] between liquid helium and the early universe arises because they both undergo phase transitions that can be considered as being of second order, describable in terms of Ginzburg-Landau theory[6]. In each case, the potential contribution to the free energy density can be written as

$$V = \alpha|\psi|^2 + \frac{1}{2}\beta|\psi|^4 \tag{1}$$

For liquid helium, the order parameter (Bose condensate wave function) ψ is given by a solution of the Ginzburg-Pitaevskii (GP) equation[7], and there is a very similar equation[8] to describe the gauge fields ψ in the cosmological situation. In both cases, the average $\langle\psi\rangle$ is zero at high temperatures but, as the system cools, a symmetry-breaking phase transition occurs at a critical temperature ($\sim 10^{27}$K for the early universe, $\sim$ 2K for liquid ^{4}He) below which $\langle\psi\rangle$ assumes finite values. Above the transition temperature, liquid ^{4}He exists in its normal (non-superfluid) phase, and behaves as a conventional liquid; below the transition, the coherence of the order parameter gives rise to a range of exotic properties such as frictionless flow, referred to collectively as superfluidity, in which the liquid behaves as though it were an interpenetrating mixture of two distinct components - a normal fluid component and a superfluid (zero viscosity) component. The early universe above its transition temperature is believed to have existed in a symmetric state, with a so-called false vacuum characterised by unified fundamental forces and the negative pressure that provides the basis for inflationary cosmologies; below the transition, the symmetry is broken, corresponding to the true vacuum and the distinction between fundamental forces (electromagnetic, gravitational, strong and weak nuclear) that are familiar features of the universe today.

As the system passes through the phase transition, an event horizon limits the size of causally connected regions of the nascent new phase (superfluid/true vacuum), giving rise to topological defects where the regions meet. Defect creation of this kind is generic to gauge theories with an elementary Higgs boson, e.g. the Standard Model and grand unified theories (GUTs); for theories with a composite Higgs boson, on the other hand, e.g. Technicolour, the cosmology has not yet been studied in detail. A defect that is a feature of many cosmological models, and which appears to have the appropriate properties for nucleating galaxies, is the cosmic string - a thin tube of false vacuum. The solutions of the GP equation for superfluid ^{4}He, corresponding to cosmic strings, are quantized vortices[5]: Zurek's suggestion[2–3] was that the postulated production mechanism of cosmic strings in the cosmological phase transition might be demonstrated and studied in the laboratory through the production of their superfluid analogue, quantized vortices, at the lambda transition.

As a cosmological model, liquid ^{4}He suffers from the disadvantages that low temperatures are required and that the generated defects cannot be observed directly. On the other hand, liquid ^{4}He also offers important advantages. In particular, compared to liquid crystals[9,10] its complex scalar order parameter ψ corresponds more closely to the most commonly considered type of cosmological field, and its extremely low viscosity makes it a more plausible model of the vacuum. Furthermore, the liquid ^{4}He used in our experiments has been prepared in a state of extraordinarily high (arguably absolute) purity[11], so that one can be entirely confident that any defect formation that occurs is intrinsic to the liquid itself, and is not associated with nucleation on impurities.

Zurek argues[2,3] that the density L of defects produced will depend on the time τ_Q taken to traverse the transition region, with

$$L = k/d^2$$

where k is the quantum of circulation in the case of ^{4}He, and the characteristic cell size d (in metres) of correlated regions is given in Ginzburg-Landau theory by

$$d \sim 5.6 \times 10^{-10} (\tau_Q/\tau_0)^{\frac{1}{4}}$$

and $\tau_0 \sim 0.85 \times 10^{-11}$ s determines the characteristic timescale of the transition. Although defects will always be generated in a passage through the transition at any finite speed, production of a large defect density requires that the transition should occur rapidly. The singularity (logarithmic infinity) in the specific heat[12] precludes the cooling of a volume of liquid helium rapidly through the lambda transition but, as Zurek pointed out, the liquid can instead be *expanded* through the transition at a speed limited, ultimately, by the velocity of first sound (i.e. ordinary sound, a pressure-density wave in which the normal and superfluid components oscillate in phase with each other). The speed at which changes in the order parameter ψ can propagate is limited by the very much smaller velocity of second sound[12] (an entropy-temperature wave in which the normal and superfluid components oscillate in antiphase), which falls to zero at the transition itself. The phase diagram of ^{4}He, and a suitable expansion trajectory, are sketched in Fig 1 (where a change in sign of the gradient of the approximately isentropic trajectory is anticipated because of the change in sign of the coefficient of expansion at the lambda transition[12]). The experiment was first attempted at Los Alamos by Shiah and Hoffer (unpublished), but with inconclusive results.

We have tested these ideas by expanding a small cell containing $\sim 10^{-3}$ kg of isotopically pure[11] liquid ^{4}He through the lambda transition. The experimental cell, whose body consists of a bronze bellows, is situated within an evacuated enclosure surrounded by a bath of He II at $\sim$ 2K. The temperature of the ^{4}He sample can be raised or lowered by means of a heater or a breakable thermal link to the bath, respectively; and the volume of the sample can be adjusted by compressing or expanding the bellows by means of a mechanical linkage to the top of the cryostat. The presence of vortices produced in the expansion is detected by their attenuation of second sound[5,12] propagated across the $\sim$ 4 mm space between a gold film heater and carbon bolometer situated within the cell.

Some typical signals are shown in Fig 2, both (a) for a time shortly after the expansion (at early times, the signals are relatively noisy on account of some microphony of the low level electronics, which are sensitive to the mechanical shock of the expansion) and also (b) at a time near the end of the measuring period. Despite the noise on the early signals, it is clear that the second sound is strongly attenuated, implying the presence of vortices. The relative signal amplitude S, after normalisation by division by the amplitude of the final signal in the series (i.e. in the virtual absence of vortices), is plotted as a function of time in Fig 3(a): the rising signal amplitude can be attributed to a corresponding decay of the initial dense vortex tangle.

In addition to the vortices produced by the Zurek mechanism[2–4], some vortices will also have been generated by more conventional hydrodynamic means. This is because the expansion of a real experimental cell is non-ideal, in the sense that some flow of liquid parallel to surfaces is bound to occur (e.g. on account of the convolutions of the bellows, and the presence of the heater and bolometer). Such flows will have exceeded the critical velocity for vortex creation[5], but only for a very short time so that the resultant vortex density is expected to be small. Fig 3(b) shows the results of a test expansion starting well *below* the lambda transition, in which the fluid flows will have been very similar to those for trajectories passing through the transition. There is no evident attenuation: although some vortices must certainly have been produced, they are undetectable in the present experiment. Expansions from very slightly (a few mK) below the transition also result in significant transient second sound attenuation, although weaker than that arising from expansions passing through the transition; the origin of the corresponding vortices remains unclear. They may perhaps be associated with the vortices[13] generated by the large fluctuations of ψ that occur in thermal equilibrium just below the transition, although recent calculations by Vinen (to be published) appear to weigh against the possibility: the resolution of this interesting question may be expected to illuminate the physical nature of the lambda transition.

It follows that the strong transient attentuation of second sound caused by expansion through the lambda transition can be taken as evidence for vortices produced through the Zurek mechanism[2–4]. The form of the subsequent vortex decay, indicated by the growing signal in Fig (3a), is very similar to that seen or discussed in earlier work in that there are two distinct decay rates[14–16], sometimes separated by a local maximum. On the assumption that the fast decay rate varies as L^{-2}, where L is the vortex line density, the initial fast rate can be used to extrapolate an estimate of the initial line density L_i immediately following the expansion: we find that $L_i \sim 10^{11}$ m^{-2}. This is a conservative estimate in that the experimental error leads to an upper bound that is larger by several orders of magnitude, and a lower bound of 5 $\times 10^{10}$ m^{-2}. Although more accurate values of L_i will be obtained when the sensitivity of the electronics to mechanical shock has been reduced, it is already clear that the density of vortices generated is very large. To put these figures into perspective, note that the production of a line density of $\sim 10^{11}$ m^{-2} by rotation[5] of a vessel of liquid ^{4}He would require an angular velocity of $\sim$ 4000 radians s^{-1}, an enormous value.

This copious production of vortices created, as predicted[2,3], by passage through the lambda transition implies, by analogy, that cosmic strings were generated in the mathematically similar second order phase transition of the early universe, and that they would therefore have been available to play the role in galaxy formation envisaged by Kibble[1].

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Figures

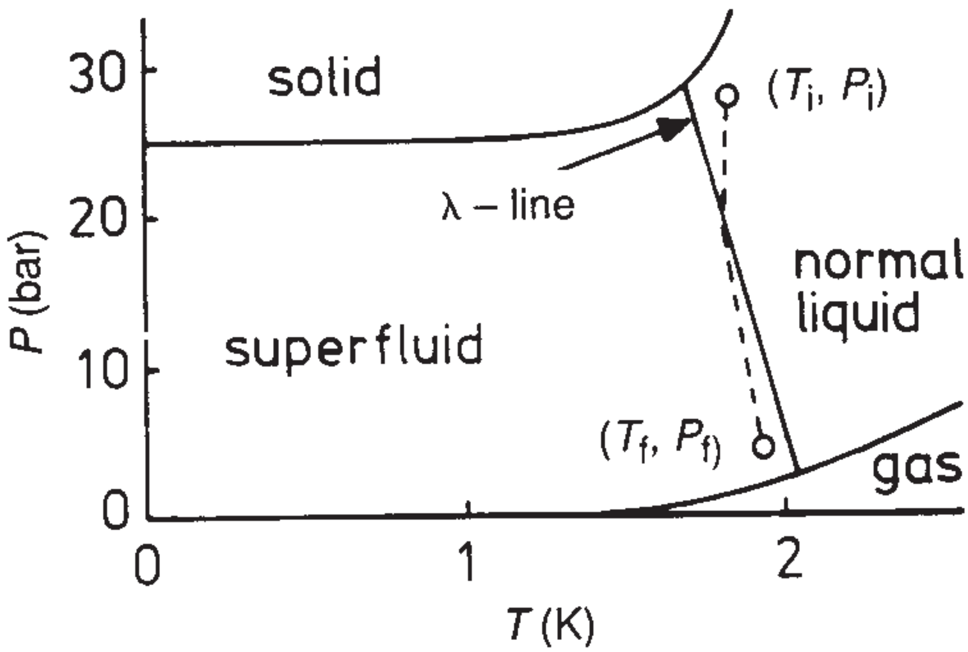

Figure 1: Sketch of expansion trajectory (dashed) through the lambda transition on the ^{4}He pressure-temperature ($P-T$) phase diagram, from initial values (T_i, P_i) to final values (T_f, P_f).

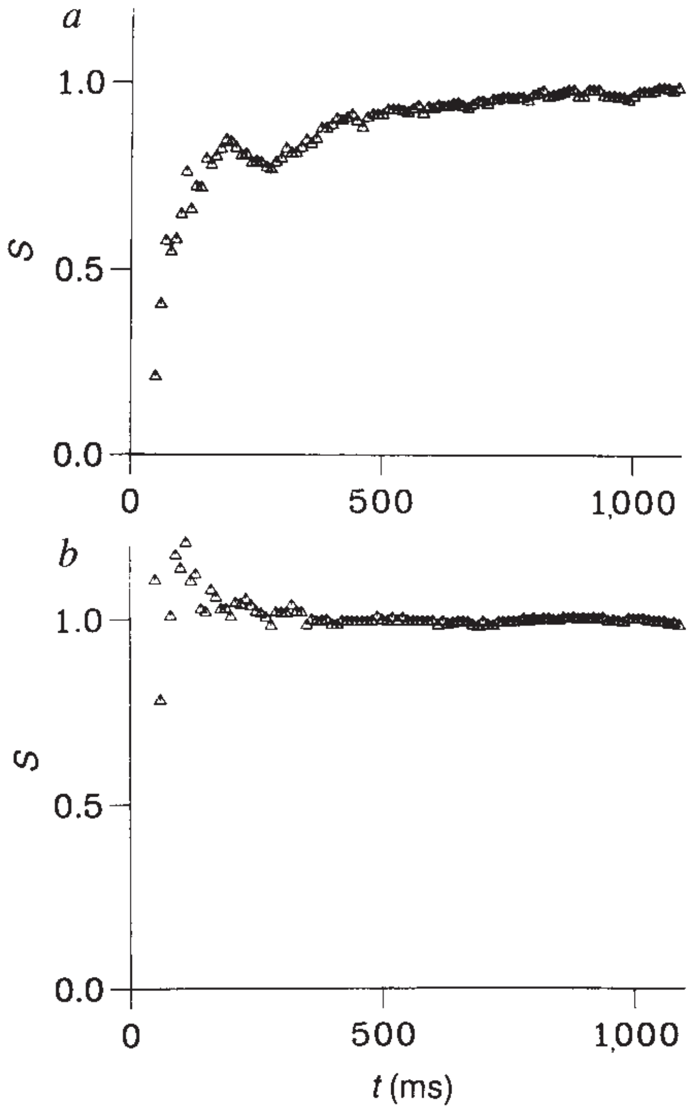

Figure 2: Typical second sound signals after an expansion through the lambda transition. Following the expansion, which is completed in $\sim$ 3 ms, a sequence of $\sim$ 100 voltage pulses is applied to the heater at 10 ms intervals, and the resultant second sound signals arriving at the bolometer are digitized and recorded on a Nicolet 1280 data processor. The signals shown were recorded at (a) 94 ms and (b) 1029 ms after the expansion. Each plot shows the change in temperature ΔT of the bolometer as a function of time t_2 after pulsing the heater, caused by the arrival of a pulse of second sound at $t_2 \sim 0.6$ ms (The large excursions near $t_2 = 0$ do not represent changes in ΔT, but correspond to a direct feed-through to the detector of the voltage pulses applied to the heater). The earlier signal, although noisy, is evidently highly attenuated compared to the later one.

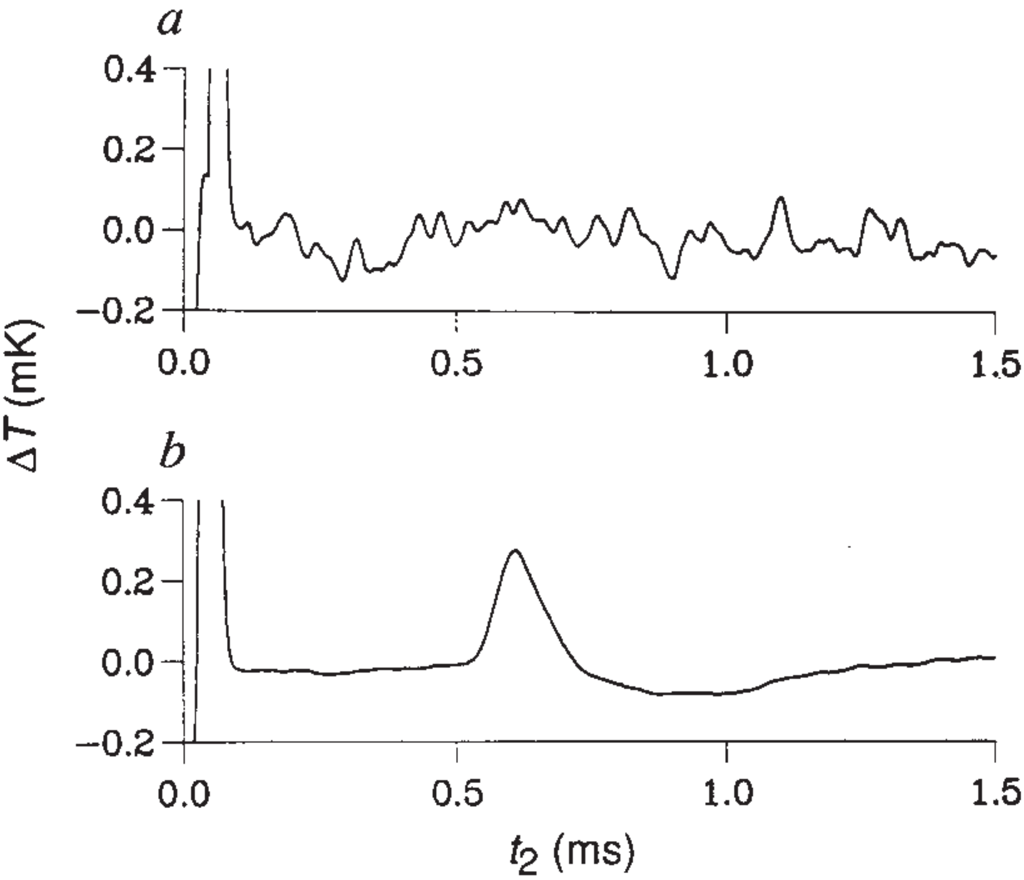

Figure 3: Evolution of the normalised second sound signal amplitude S as a function of time t: (a) following an expansion through the lambda transition from starting temperature and pressure $T_i = 1.81$ K, $P_i = 29.6$ bar to final values of $T_f = 2.04$ K, $P_f = 6.9$ bar; (b) following a test expansion, *not* through the lambda transition, but lying wholly below it, with $T_i = 1.58$ K; $P_i = 23.0$ bar; $T_f = 1.74$ K; $P_f = 4.0$ bar.