Laboratory simulation of cosmic string formation in the early Universe using superfluid ^{3}He

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TOPOLOGICAL defects in the geometry of space–time (such as cosmic strings) may have played an important role in the evolution of the early Universe, by supplying initial density fluctuations which seeded the clusters of galaxies that we see today[1]. The formation of cosmic strings during a symmetry-breaking phase transition shortly after the Big Bang is analogous to vortex creation in liquid helium following a rapid transition into the superfluid state; the underlying physics of this cosmological defect-forming process (known as the Kibble mechanism[1]) should therefore be accessible to experimental study. Superfluid vortices have been observed in ^{4}He following rapid quenching to the superfluid state[2], lending qualitative support to Kibble's contention that topological defects are generated by such phase transitions. Here we quantify this process by using an exothermic neutron-induced nuclear reaction to heat small volumes of superfluid ^{3}He above the superfluid transition temperature, and then measuring the deficit in energy released as these regions of normal liquid pass back into the superfluid state. By ascribing this deficit to the formation of a tangle of vortices, we are able to infer the resulting vortex density; we find that this agrees very well with the predictions of Zurek's modification[3] of the original Kibble mechanism[1].

In comparison with superfluid ^{4}He and liquid crystals, superfluid ^{3}He provides the ideal system for modelling the formation and evolution of topological defects remaining from the cascade of symmetry-breaking phase transitions which the Universe is believed to have undergone shortly after the Big Bang. In superfluid ^{4}He only gauge symmetry is broken, and in liquid crystals only orbital rotation symmetry is broken. However, owing to the spin and orbital angular momentum properties, ^{3}He shows a superposition of broken spin rotation, broken orbital rotation and broken gauge symmetries ($SO3^S \times SO3^L \times U(1)$) which provide a much closer approximation to the superposition of broken rotational and gauge symmetries used to describe the Universe. In fact the analogies between the structure of the Universe and of superfluid ^{3}He go further. Not only is the symmetry of the coherent quantum state of the superfluid analogous to the quantum vacuum of the Universe, but the excitations and collective modes of the superfluid have analogies with the fundamental particles bosons and fermions (ref. 4). Finally, various types of linear defects (vortices), point defects (monopoles) and textures may be generated in superfluid ^{3}He, in analogy with the various types of defects proposed for the structure of Universe.

The Kibble mechanism for vortex creation during phase transitions[1] is illustrated schematically for our experiment in Fig. 1. After a sudden local heating, the ^{3}He recools through the transition to the superfluid state. During this process, separate superfluid regions are independently nucleated with random orientations of the order parameter in each domain. As the domains grow and make contact with their neighbours, the resulting superfluid cannot be uniform. The subsequent order-parameter 'glass' forces a distribution of topological defects leading to a tangle of quantized vortex lines.

The size of the initial domains depends strongly on the rapidity with which the transition is traversed. According to Zurek[3] the distance between the ensuing vortices β is given approximately by $\beta = \xi_0(\tau_Q/\tau_0)^{1/4}$, where ξ_0 is the coherence length at zero temperature, τ_0, the coherence length divided by the Fermi velocity, (ξ_0/v_F), is the characteristic time of the superfluid, and τ_Q is the characteristic time for cooling through the phase transition.

Superfluid ^{3}He has the further advantage as the working substance in that it allows a very precise localized crossing of the phase transition to be generated by nuclear reaction[5], which avoids the more violent global processes used for earlier experiments on ^{4}He and liquid crystals[2,6]. The ^{3}He nucleus has a very high cross-section for neutrons via the process: $n + {}^3He \rightarrow {}^3H + p$. This process also liberates a precise energy of 764 keV which is initially shared by the product proton and tritium nucleus. The mean free path of the products in the liquid is limited to around 30 μm as the kinetic energy is rapidly thermalized with the creation of a cloud of quasiparticle excitations and excited ^{3}He atoms providing enough heat to warm a small volume of the liquid to above the superfluid transition. The volume of normal liquid ^{3}He then rapidly recools on a timescale of 1 μs or less.

In a companion experiment[7] Ruutu *et al.* have shown directly that vortices are indeed created in superfluid ^{3}He by this process. They observe unambiguous vortex nucleation triggered by neutron irradiation in a rotating experiment at higher temperatures. In the present experiment we measure how much of the energy released is retained in the liquid in the form of a vortex tangle. As we know the energy of a vortex per unit length, we can go further and make a quantitative calculation of the vortex density remaining which we can compare with Zurek's prediction.

The present measurements are made close to the lower limit to

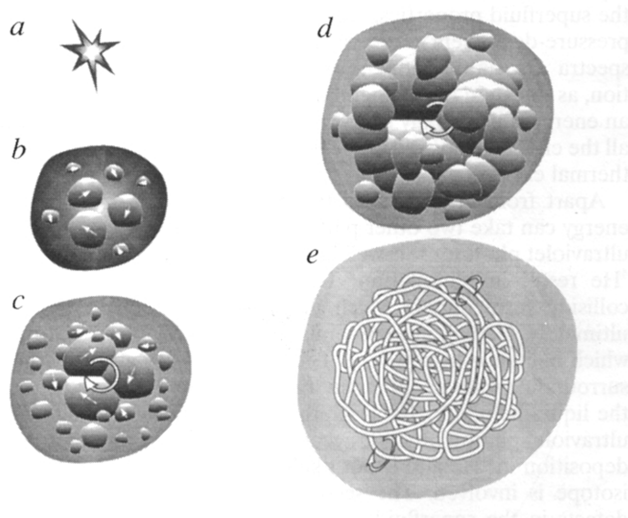

FIG. 1 Schematic view of the creation of a tangle of linear singularities by the nucleation of independent ordered regions as a system passes through a phase transition. In the superfluid ^{3}He context; at *a*, a neutron has struck a ^{3}He nucleus initiating the process $n + {}^3He \rightarrow {}^3H + p$, liberating 764 keV of energy and creating a small region of very high temperature in the liquid. At a later time *b* the hot region has expanded and cooled to near the transition temperature. Small regions of superfluid are independently nucleated each having a different value of the order parameter, as shown by the small arrows. At *c* the three central ordered regions now touch. Although the order parameter may bend to accommodate the boundaries, a full 2π change around the triple contact point remains. This is a vortex. At *d*, many more regions have been nucleated and overlap, and along the grain boundaries a whole tangle of vortex lines is created. Finally, at *e* the hot bubble has cooled entirely through the transition and only the tangle of vortices remains.

which superfluid ^{3}He can be cooled (around 0.1 T_c, where T_c is the superfluid transition temperature). At such temperatures the few remaining thermal quasiparticles form an extremely dilute non-interacting gas. It is the mutual friction provided by the quasiparticles which mediates the evolution and gradual disappearance of vortices. Therefore, under our conditions, after a neutron event, the local high density of quasiparticles falls very rapidly to the vanishingly small background density. Thus the vortices are only exposed to appreciable mutual friction for a very short time and we estimate that almost all the initial vortex density should survive.

The experiment is made at temperatures down to 160 μK in the Grenoble nuclear refrigerator. The detector is a Lancaster-style quasiparticle detector[8], in the form of a 0.15 cm^3 copper-walled enclosure containing superfluid ^{3}He, connected via a 60-μm hole to a larger volume of superfluid at a temperature below 100 μK. Energy deposited within the enclosure warms the superfluid by the creation of quasiparticle excitations. The resulting temperature rise is detected by a sensitive vibrating-wire resonator. The temperature of the enclosure then recovers as quasiparticles escape through the small hole over a time determined by the geometry. A particle scattering event inside the detector is observed on the temperature record as a sharp temperature rise followed by a slow recovery over about 60 s.

The energy sensitivity of the detector is calibrated with a second vibrating-wire resonator which serves as a heater (which, when intensely oscillated, creates quasiparticle–quasihole pairs in the superfluid). We can simulate a scattering event by exciting the 'heater' resonator to introduce a measured quantity of energy during a time which is short compared to the detector recovery time, allowing a rather accurate energy calibration of the detector.

An external AmBe (americium–beryllium) neutron source irradiates the cell with a very low flux of neutrons. The temperature trace is recorded, and the events analysed and presented as a spectrum of counts versus energy. The whole procedure is repeated at three different pressures for the superfluid (because the superfluid properties, such as gap and coherence length, are pressure-dependent). We observe a clear peak in the energy spectra associated with the $n + {}^3He \rightarrow p + {}^3H + 764$ keV reaction, as shown in Fig. 2. Significantly, however, the peak occurs at an energy substantially below the canonical 764 keV. Clearly not all the energy deposited in the detector by the reaction appears as thermal excitations.

Apart from appearing as thermal excitations, the deposited energy can take two other paths. First, the energy can appear as ultraviolet photons. It is well known that collision events in liquid ^{4}He result in scintillation. The ^{4}He ions produced after the collision form dimers which decay by a cascade of processes ultimately leading to the emission of ultraviolet photons to which helium is transparent. These photons are absorbed in the surrounding walls and their energy is prevented from returning to the liquid helium by the large thermal boundary resistance. The ultraviolet photon process[9] accounts for 6–8% of the total energy deposition in ^{4}He and is not likely to be at all sensitive to which isotope is involved. The second path involves the creation of defects in the superfluid, of which only vortices can acquire a significant energy.

As we can be certain that the ultraviolet losses are very insensitive to pressure, we can subtract the ultraviolet component from the measured energy missing from the initial 764 keV. We find that the remaining energy still unaccounted for is 60, 70 and 125 keV at the three pressures measured, 0, 6 and 19.4 bar, respectively. We believe that this remaining energy deficit has been retained in the liquid by the creation of vortices.

To calculate the initial separation of the vortices, β, we need to know, first, the volume of liquid V heated above the transition, second, the energy per unit length of the vortex, and third, for comparison with Zurek's predictions, we also need an estimate of the time for cooling through the transition, τ_Q. The energy per unit length of a vortex is approximately $(\rho/4\pi)(\hbar/2m_3)^2 \ln(\beta/\xi_0)$ which

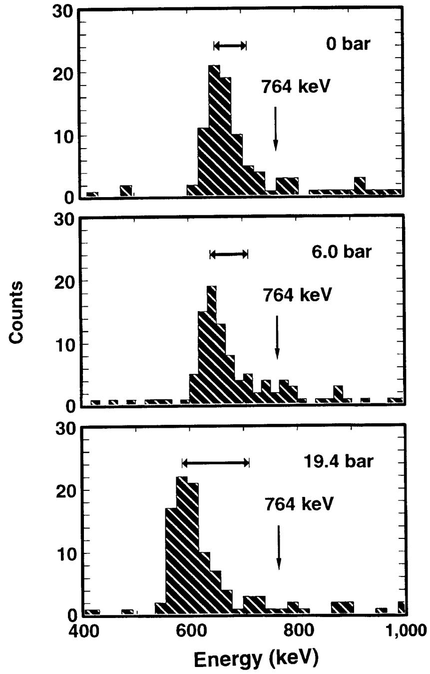

FIG. 2 The energy spectra in counts versus energy deposited into the quasiparticle system of superfluid ^{3}He under neutron irradiation at three pressures of the liquid. The peak from the neutron-capture process $n + {}^3He \rightarrow {}^3H + p$ is clearly visible. This reaction is exothermic, liberating 764 keV of energy. Approximately 7% of this energy is released as ultraviolet photons which are lost from the helium. However, as shown in the figure by the double-ended arrow, a significant fraction of energy is 'missing', a quantity which increases with pressure. It is this energy, which does not produce thermal excitations, that we assume remains in the liquid in the form of a vortex tangle.

is about 0.5 keV mm^{-1} at 0 bar. The quantities V and τ_Q are sensitive to the details of the process whereby the kinetic energy of the released proton and tritium nucleus is converted to excitations of the fluid. This process is very poorly understood. However, we can make estimates with the following very simple model: the energy E is assumed to be deposited at a point in the fluid, which subsequently cools by thermal diffusion with the diffusion constant D taken to be equal to that of the ^{3}He liquid at the superfluid transition temperature T_c. These assumptions yield a spherical volume of normal fluid with radius $R \approx 0.4(E/CT_c)^{1/3}$, where C is the liquid heat capacity just above T_c and $E = 710$ keV is the deposited energy after subtraction of the ultraviolet losses. The characteristic cooling time is then given by $\tau_Q \approx R^2/4D$. This yields normal volumes with radii of 25, 16 and 11 μm and cooling times of 0.23, 0.46 and 1.1 μs for the measured 0, 6 and 19.4 bar pressures, respectively.

The coherence length in superfluid ^{3}He for the three pressures considered here is 770, 390 and 210 Å. Our measured value of the ratio β/ξ_0, (the separation of the vortices in coherence-length units) is thus found to have a pressure independent value of about 8. We can compare this ratio with the appropriate value of the equivalent parameter $(\tau_Q/\tau_0)^{1/4}$ in the Zurek model. Using the simple model of diffusion cooling for the hot volume considered above, we find a value of this parameter varying from 4 to 7 over the pressure range investigated.

Given the simplicity of the assumptions and approximations used, the agreement between our measured values of β/ξ_0 and the corresponding Zurek parameter, $(\tau_Q/\tau_0)^{1/4}$, is surprisingly close. Because the whole process of the conversion of the initial reaction energy into thermal energy is at present poorly understood, it is very difficult to make an accurate estimate of the errors involved in the simple model we have used for the cooling process. Furthermore, the prediction $\beta/\xi_0 = (\tau_Q/\tau_0)^{1/4}$ from the Zurek model is only qualitative.

This close agreement, however, does confirm that a fast cooling through the superfluid transition indeed creates a residual density of vortices as foreseen in Zurek's model of the Kibble mechanism. That the observed vortices are further spaced than the theory suggests may simply be a reflection of the approximations made both in deducing the value from the data and estimating the equivalent number from Zurek's expression. Why the observed separation, β/ξ_0, is apparently independent of pressure is not clear at present. Finally, if indeed analogous topological objects have once existed or even survive in the Universe, then we have taken the first tentative steps with superfluid ^{3}He towards the quantitative modelling of their formation. □

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