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Vortex creation in a fast adiabatic expansion through the lambda transition

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Copious vortex line creation in a fast (~ 3 ms) adiabatic expansion of a volume of liquid ^{4}He through the lambda transition has been observed. The maximum line density, inferred from measurements of second sound attenuation, is found to be much larger than that in a comparable expansion from just below the lambda line. The phenomenon was predicted by Zurek who proposed it as a model of cosmic string creation in the false vacuum/true vacuum phase transition of the early universe.

1. INTRODUCTION

The superfluid transition in liquid ^{4}He (lambda transition) has been proposed [1] as an experimentally accessible model of the phase transition from false vacuum to true vacuum that is believed to have occurred when the universe was young ($\sim 10^{-34}$s after the big bang) and hot ($\sim 10^{27}$K). The lambda transition can be considered as a phase transition of second order, describable in terms of Ginzberg-Landau theory [2], with a potential contribution to the free energy of form

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

where the complex order parameter ψ is given by a solution of the Ginzberg-Pitaevskii equation. Below the lambda transition, $V(\mathrm{Re}(\psi), \mathrm{Im}(\psi))$ takes on the same "sombrero hat" shape as the corresponding cosmological free energy expressed in terms of Higgs fields. In both cases, a fast passage through the phase transition is expected to yield topological defects, because of an event horizon that causes the order parameter of the nascent superfluid (true vacuum) to be spatially incoherent. In the cosmological scenario, this is the Kibble mechanism [3] for creation of the defects, e.g. cosmic strings (thin tubes of false vacuum), that may have played an important role in seeding galaxy formation [4]. The analogue of cosmic strings, for the case of liquid ^{4}He, is quantized vortices [5]. Remarkably, therefore, an investigation of vortex creation at the lambda transition, like earlier investigations of defect production at phase transitions in liquid crystals [6], [7] may be expected to yield information of cosmological significance.

In this paper, we report the preliminary results of an experiment designed to test Zurek's predictions [1] by seeking evidence for vortices created when a volume of liquid ^{4}He is expanded rapidly through the lambda transition.

2. EXPERIMENTAL DETAILS

A sample of $\sim 10^{-3}$ kg of isotopically pure [8] liquid ^{4}He is held within a cell closed by a bronze bellows arrangement, inside an evacuated enclosure, immersed in a surrounding bath of He II at ~ 2.0K. The temperature and volume of the sample can be adjusted respectively with the aid of a breakable thermal link to the surrounding bath, and by means of an external force applied to the bellows through a mechanical linkage from the top of the cryostat. In typical operation (sketched in Fig 1(a)), the cell is expanded from an initial pressure $P_i = 29.6$ bar and temperature $T_i = 1.81$ K, through the lambda transition, to final values of $P_f = 6.9$ bar and $T_f = 2.04$ K, in a time $\tau_e \sim 3$ ms. The resultant vortices are detected through their attentuation of a sequence of single pulses of second sound propagated over 4.0 mm between a heater/bolometer pair within the cell. Typically, some 170 such pulses are recorded by a Nicolet 1280 data processor in a single time series during 1.7 s immediately following the expansion.

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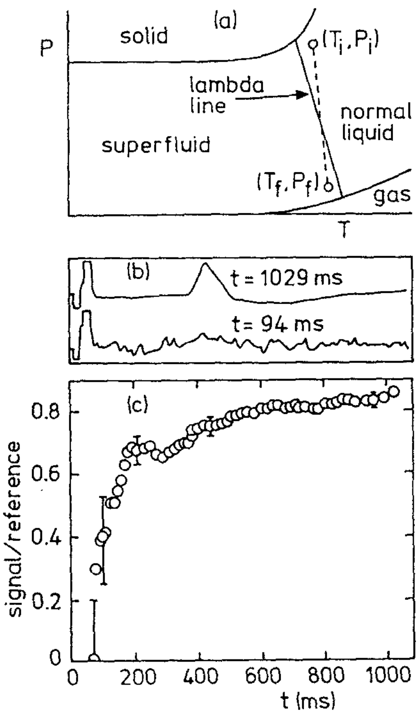

Figure 1. (a) Sketch of expansion trajectory (dashed) on ^{4}He phase diagram. (b) Second sound signals (initial transients are from the heater pulse). (c) Evolution of normalised second sound amplitude following the expansion at $t = 0$.

3. RESULTS

Examples of second sound signals at two different times are shown in Fig 1(b). Although signal/noise just after the expansion is adversely affected by mechanical vibration, it is immediately evident that the signal is strongly attenuated. The signal height, normalised by a reference signal at $t \sim 600$ s, is plotted as a function of time in Fig 1 (c); the error bars indicate peak-to-peak noise on the signals. For comparison, expansions have also been made starting with (T_i, P_i) below the transition: here, too, attentuation of the second sound signal is observed, but the effect is much less pronounced (typically signal/reference $\sim$ 0.75 at 100 ms) than for trajectories passing through the transition.

4. DISCUSSION

The relatively weak transient second sound attenuation produced by expansions from *below* the lambda transition may be presumed to result from the growth of pre-existing vortices [9] due to the fluid flow components parallel to surfaces that inevitably arise in a real experimental cell. The strong transient attenuation seen after expansions *through* the lambda transition (Fig 1) can be regarded as evidence for vortex generation through the Zurek mechanism [1]. It is hoped that improved data will permit a reliable extrapolation to determine the vortex line density immediately after the expansion: efforts towards this end are currently in progress.

5. CONCLUSION

The preliminary data shown in Fig 1 (b) and (c) provide encouraging support for Zurek's prediction [1] and thus, in common with the liquid crystal experiments, for the ideas underlying the Kibble mechanism [3, 4] of galaxy formation.

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