Probing "Cosmological" Defects in Superfluid ^{3}He-B with a Vibrating-Wire Resonator

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We report on the observation of an anomalously high damping measured by a vibrating-wire resonator (VWR) immersed into superfluid ^{3}He-B at ultralow temperatures. The observed dissipation is orders of magnitude above that corresponding to friction with the dilute normal fraction and superfluid vortices. A clear pinning behavior is also observed, as well as a strong magnetic field dependence. Our analysis points to the interaction of the VWR with a planar topological defect, analogue to cosmological vacua defects, as proposed by Salomaa and Volovik.

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Superfluid ^{3}He is certainly among the most complex systems in condensed matter which are successfully described by a comprehensive theory. The complexity of its superfluid order parameter makes ^{3}He the standard condensed matter analogue to cosmological phenomena as vacuum symmetry breaking, particle creation, cosmic string properties, etc. [1–3]. A myriad of topological, as well as nontopological defects, is hosted by the superfluid vacua of both A and B phases, such as linear defects (vortices), **n** solitons, vortex sheets, boojums, and spin-mass-vortices [see, e.g., [4,5]]. One-dimensional topological defects in the form of quantized vortices in ^{3}He-B in particular can be detected and created by vibrating-wire resonators (VWRs) [6,7]. Two-dimensional defects, however, are much less studied. A classification of planar topological defects was published [8] in 1978 and planar nontopological defects [9] in 1988. More recently a NMR π shift in an experiment based on a superfluid ^{3}He-B gyroscope has been discussed in terms of planar topological defects [10]. The presence of nontopological defects in the gyroscope channel was given as a possible explanation.

In this Letter we report on the first observation of the interaction of a VWR with an extremely energetic defect. The associated energy points to a planar defect with a thickness of about the superfluid coherence length ξ_0, attached along the VWR. Among the list of possible defects, only the "cosmological" planar defect [9] can be accused for our results.

The VWRs used are thin superconducting wires of thickness of a few μm, bent into a semicircular shape of about 5 mm in diameter and resonating mechanically at about 500 Hz. In the presence of a constant magnetic field, and by applying a small ac drive current ($\sim$5 nA) at a frequency close to the wire's mechanical resonance frequency, the VWR is brought to oscillate. The amplitude of oscillation can be detected by measuring the voltage induced by the motion of the superconducting loop through the applied magnetic field. The measurement of the width Δf_2 of the resonance in frequency space provides a measurement of the damping experienced by the VWR ("damping" will therefore further be expressed in Hz). A typical value of Δf_2 at 120 μK is a fraction of a Hz, depending on the VWR's exact geometrical features. In normal as well as in superfluid ^{3}He, the strong temperature dependence of Δf_2 makes VWRs commonly used thermometers [11,12].

If immersed into superfluid ^{3}He-B at ultralow temperatures, the VWR experiences a damping due to collisions with the dilute quasiparticle gas of the remaining normal fraction. The non-Newtonian dispersion relation in the superfluid, as well as the possibility of Andreev scattering of the quasiparticles, cause this thermal damping to be nonlinear in velocity [11]. At velocities below a few mm/s, the force-velocity curve can nevertheless be well approximated by a linear relation and the resonance curves may hence be considered to be Lorentzian.

The experimental volume (Fig. 1) is a copper cell containing superfluid, connected to the large outer bath by a small orifice. Such a cell, containing one or more VWRs, is in our setup usually aimed for bolometric particle detection, and, in particular, for the search of nonbaryonic dark matter [13]. One of the two VWRs contained in this particular bolometric cell, denoted as wire T (NbTi, 4.5 μm diameter, 4.7 mm leg spacing) serves as a sensitive

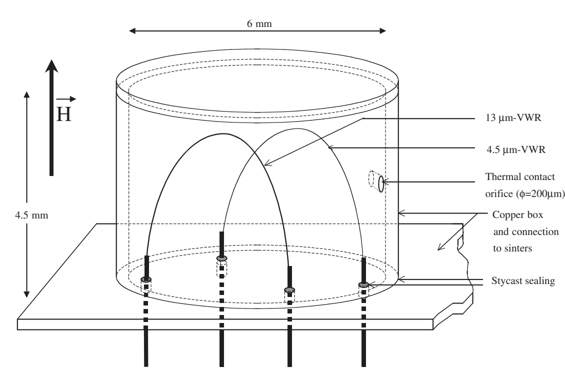

FIG. 1. Bolometric cell containing superfluid ^{3}He. The $\phi =$ 4.5 μm-VWR (T-VWR) serves for thermometry and the $\phi = 13$ μm-VWR (heater) for the bolometric calibration.

thermometer in the bolometric setup that can detect energy depositions as low as 1 keV at base temperatures of 120 μK. The second VWR visible in Fig. 1, denoted as the heater wire, is slightly larger (NbTi, 13 μm diameter, 5.0 mm leg spacing) and serves for the energy calibration of the bolometric cell. Driven at its resonance with a high drive over a short time, the heater wire allows to release a well-controlled amount of energy to the superfluid by friction with the quasiparticles as well as pair breaking. Because of the high Kapitza resistance between the superfluid and the wires, and because these are superconducting, no Joule heating of the liquid occurs during such heater pulses.

In this Letter, however, we report on a previously unobserved anomalous damping behavior on the T-VWR that can neither be explained by thermal quasiparticle damping nor by any simple experimental problem like mechanical touching.

In the following we shall refer to the well-known quasiparticle dominated damping [11], exponentially decreasing with temperature, as normal, in contrast to the here reported anomalous damping behavior. In 6 out of 22 experimental runs (adiabatic nuclear demagnetizations of the copper stage), i.e., with an occurrence of about 30%, the T-VWR displayed very high damping values of up to 200 Hz, constant in time and temperature independent. In all of these anomalous runs, this higher value of Δf_2 of the T-VWR was in clear contradiction with the thermal damping experienced by all other wires present: 3 outside the cell and 1 (the heater wire) inside. At the usual experimental magnetic field of 100 mT, the shape of the resonance curve remained still Lorentzian, however, with only a constant and large extra damping term adding to the thermal one

$$\Delta f_2 = G_0 \exp(-\Delta/k_B T) + \Delta f_2^{\mathrm{anom}} \qquad (1)$$

anomalously damped.

While at fields at about 100 mT, $\Delta f_2^{\mathrm{anom}}$ is drive amplitude independent, i.e., all friction obeys viscous laws; at magnetic fields below 60–70 mT the anomalous resonance curves are observed to rapidly collapse on decreasing the drive current below some critical value (Fig. 2). The strongly nonlinear force-velocity relation of the VWR at resonance, as displayed in Fig. 3, suggests that the VWR is pinned at low drive forces F_p while the lowering of the resonance frequency seen in Fig. 2 indicates a large extra mass is being dragged. The force-velocity curves (Fig. 3) are not hysteretic; e.g., by unpinning the wire the source of the pinning is not destroyed nor modified. Furthermore, F_p is constant in time.

The magnetic field dependence of F_p for 2 anomalous experimental runs is shown in Fig. 4. When the field was reduced, F_p increased dramatically. With further lowering the field the VWR abruptly depinned at the fields shown by vertical arrows. After depinning, the VWR displayed a

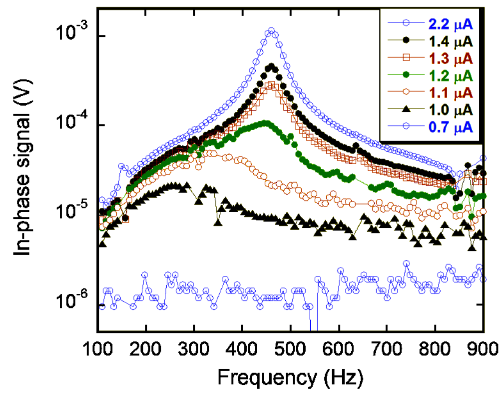

FIG. 2 (color online). Collapse of the resonance line on lowering the drive at fields below 60–70 mT. This behavior was observed in all of the 4 anomalous experimental runs in which we went to lower fields. The resonance frequency decrease at low drives indicates the enhancement of the oscillating mass.

completely normal damping behavior ($\Delta f_2 < 1$ Hz), in agreement with the quasiparticle friction experienced by the surrounding VWRs. Setting the field back to the initial value did not restore the anomalous behavior. This could only be achieved by warming up the system above the superfluid transition temperature.

The explanation for such an unusual behavior of a mechanical resonator has, before concluding on new physics, to be sought in experimental problems. On exchanging the complete electronic setup between the VWRs, no difference was observed in the anomalous runs. The strong and very hysteretic magnetic field dependence, as well as the nonregular appearing of the effect following the adiabatic demagnetization cooldowns to the superfluid state, rule out all mechanical problems, like touching of the VWR with a surrounding solid object, the presence of a dust grain, friction due to the proximity of a cell wall, or friction with a lose NbTi filament at one VWR leg. Hypothetically, the origin of the effect could be thought to be related to trapped magnetic flux lines inside the NbTi

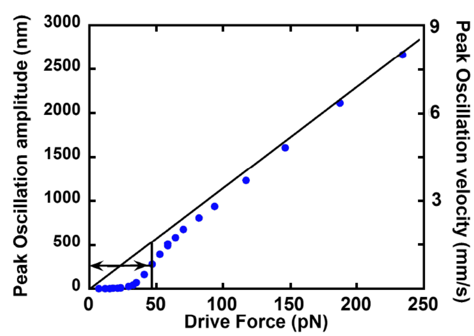

FIG. 3 (color online). Strongly nonlinear force-velocity relation of anomalously damped T-VWR at 55 mT. The collapse of the response at low drives suggests a pinning of the wire. F_p is defined as the force at which the VWR response deviates from the linear high velocity extrapolation by a factor 2.

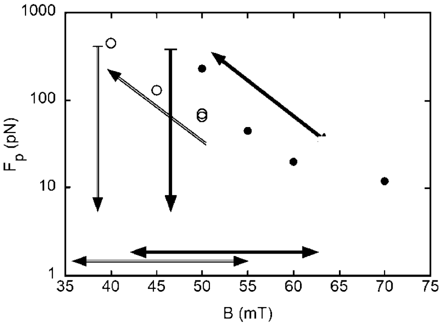

FIG. 4. Dramatic increase of the pinning force as the field is lowered to a critical field. The vertical arrows indicate the fields at which the T-VWR was completely trapped, before the spontaneous and sudden disappearance of the anomalous damping or pinning effect.

wire of VWR. Nevertheless, it is difficult to explain the large amplitude of the effect by this mechanism.

To rule out all possible mechanical-touch scenarios, we have made an experiment with local heating of our bolometric cell. In usual conditions, the heating pulses by the heater VWR are used for the thermometric and bolometric calibration of the setup for particle detection [14]. By briefly injecting several MeV in the cell, a transitory temperature increase of a few μK of the cell is achieved. In one anomalous experimental run at 100 mT, while the T-VWR displayed an anomalous damping of $\Delta f_2^{\mathrm{anom}} = 80$ Hz, we produced a strong heating pulse by applying drive currents of 35 mA over 2 minutes to the heater VWR, which transitorily increased the strong warm-up of the outer temperature inside the cell to the vicinity of T_c. While all VWRs subsequently monitored the temperature relaxing back to their previous base value on a time scale of 20 minutes, the T-VWR relaxed to another high anomalous value, this time twice bigger, of about $\Delta f_2^{\mathrm{anom}} = 150$ Hz. We then produced a second heater pulse of the same intensity. In the subsequent cooldown, the anomalous damping had completely disappeared and the T-VWR displayed the normal, quasiparticle dominated damping just as all other VWRs present. This observation demonstrates that the additional damping term can be changed by a brief heating to the superfluid transition of the experimental ^{3}He sample. It has to be emphasized that while a temperature rise from 0.1 to 1 mK has dramatic effects on the ^{3}He, it is absolutely insignificant for all other materials involved.

We are hence led to question the possibility of an effect originating directly from the superfluid ^{3}He. Quantum vortices are not possible candidates since their interaction with VWRs only leads to a slight increase of the VWR dissipation above a finite velocity threshold [7], with a velocity dependence very different from our findings. Further, quantum vortices are, in the absence of counterflow, short-lived objects [15], whereas the observed effect is time independent on the scale of at least 1 d. Bigger topological objects as, e.g., spin-mass vortices as observed in Helsinki [16] have dimensions similar to the VWR's ($t \sim 10$ μm) but are, because of the weakness of the dipole-dipole interaction, too soft to be able to produce the pinning reported.

Several nontopological but very energetic planar defects have been classified theoretically by Salomaa and Volovik and named "cosmological" for their formal analogy with defects considered in cosmology [9]. In the 3×3 complex matrix representation of the superfluid ^{3}He order parameter, two states identical except by an odd number of matrix element sign changes have physically identical properties but cannot transform continuously into each other: their interface forms a solitonlike planar defect. Being nontopological, this type of defect is, in principle, not stable. Thuneberg, however, suggested that some of these types of defects can be locally stable [17]. Such a half-quantum defect carries a very high energy and is, in general, disappearing rapidly if no boundary conditions prevent it from doing so.

Assuming ^{3}He to be normal-like in the core of these defects, we can estimate their surface tension as $\sigma = n_3 \Delta_0 \xi_0$ (where n_3 is the numerical ^{3}He density, Δ_0 the superfluid gap, and ξ_0 the superfluid coherence length), yielding about 4×10^{-8} J $\cdot$ m^{-2} at 0 bar. Integrating σ over the length of the VWR yields a pinning force of up to a few 100 pN, which corresponds indeed to our experimental results. This simple estimation again rules out a vortex scenario, since the vortex energy is proportional to $\Delta_0 \xi_0^2$, it would require an unrealistic number of vortices along the VWR of order $\frac{L}{\xi_0} \approx 10^7$ to produce such a friction.

The oscillation amplitudes $X_p(B)$ at which the pinning or unpinning of the T-VWR is observed in anomalous runs are typically of the order of a few ξ_0, as shown in Fig. 3. If one pictures the domain wall in the plane of the VWR as represented in Fig. 5, the resonator is pinned for small excitation drives, since the thickness of the defect ($\sim \xi_0$) is much smaller than the wire diameter. The pinning is likely to be due to sites of surface roughness on the VWR.

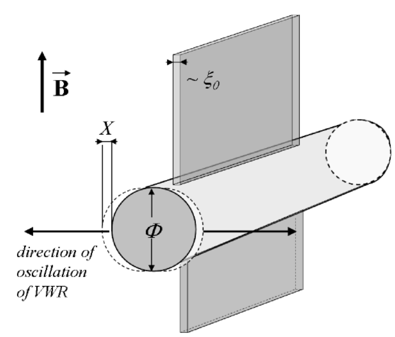

FIG. 5. Suggested scenario of the domain wall in the superfluid, when present on the T-VWR. The defect thickness is of the order of $\xi_0 \sim 90$ nm. Note that the oscillation amplitude X is generally much smaller than the VWR diameter $\Phi = 4.5$ μm.

For bigger excitations, the VWR is unpinned and the large friction experienced at the position of rest is averaged over the whole period. Considering $R = L/2$ as one relevant length scale of the defect, where $L \approx 5$ mm is the interleg spacing of the VWR loop, and equating the pinning energy $E_p = X_p \times F_p$, we obtain the characteristic length scale

$$\lambda = \frac{E_p}{\sigma R}, \tag{2}$$

over which the surface tension of a cosmological defect appears. With typical values of X_p and F_p as, e.g., in Fig. 3, one finds λ of the order of 100–200 nm. This value is close to both X_p and the surface roughness of the NbTi VWR surface, which is estimated to about 3%–5% of the wire diameter $\phi = 4.5\ \mu$m, leaving the exact interpretation of the friction process on the domain wall open.

The experimental magnetic fields of 35 to above 100 mT used in our experiment are higher than in most comparable VWR experiments at ultralow temperatures. The key feature of the observed anomalous behavior of the T-VWR resides in the strong field dependence of the pinning effect, which still awaits theoretical explanation. A possible explanation would be that the cosmological defect is stabilized at finite fields above about 40 mT. By decreasing the magnetic field to this critical value, the defect could be thought to soften, producing an enhancement of the dissipation in analogy to the peak effect commonly observed in the vortex array of type-II superconductors. At a field of the order of 100 mT the defect can be thought to be very rigid, and therefore not to oscillate with the VWR and interact by simple friction. With decreasing magnetic field, the defect becomes softer and surface waves at the VWR frequency are responsible for the large dissipation. Finally, at a field of about 40 mT (depending on the geometry of domain wall), the planar defect resonates at the VWR frequency, until finally it disconnects from the VWR surface.

In [10] a statistically observed π shift in experiments based on a superfluid ^{3}He-B gyroscope was reported. Such a shift indeed could be explained by a planar defect, crossing the superfluid path of the gyroscope. The authors suggested therein the cosmological planar defect as a possible explanation. However, in contrast with our situation, this experiment was performed at zero magnetic field. The same type of planar defect may be stable in the thin channels of the gyroscope at zero field, while in our conditions of a larger (~mm) experimental cell, the cosmological planar defect loses its stability below 40 mT.

In conclusion, we have observed, in a mechanical oscillator technique in superfluid ^{3}He-B, a strong damping and pinning anomaly, which points to the interaction of the resonator with cosmological planar defects of the superfluid. The properties of these should be the target of future theoretical and experimental studies.

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