Experiments with atomic Bose-Einstein condensates which are effectively confined in two dimensions offer the opportunity to study two-dimensional vortex dynamics in a real physical setting. In most previous studies vortices fill the system. In this paper we use the classical point-vortex model to model the time evolution of a cluster of quantum vortices (with close to zero net polarity) which is initially at the centre of a homogeneous condensate and is free to spread out in regions of space which are initially vortex-free. We find that this spreading motion consists of the combination of two effects: the rapid evaporation from the cluster of small vortex dipoles (vortex-antivortex pairs) and the slower enlargement of the remaining region of vorticity. The latter is akin to a diffusion process controlled by the quantum of circulation. Using the Gross-Pitaevskii equation for a homogeneous zero-temperature condensate, we determine that the sound waves and vortex annihilation do not affect this phenomenon. We also compare our results to 3D simulations of the diffusion of a random tangle of quantised vortices. Finally, we comment on the experimental realization of the phenomenon in a box-trapped condensate.
Aspects of quantum turbulence in the condensate model

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We use the Gross-Pitaevskii equation to get insight into two problems: turbulence during a thermal quench and turbulence near a rough boundary. In the first problem, we study the formation and the decay of a turbulent tangle of vortices which is created in the evolution of a Bose gas from highly nonequilibrium initial conditions as in the Kibble-Zurek mechanism. By analysing the vortex line density, the energy spectrum and the velocity correlation function, we determine that the turbulence resulting from a thermal quench lacks the coherent structures and the Kolmogorov scaling (typical of both ordinary classical fluids and of superfluid helium when driven by grids or propellers). Instead, thermal quench turbulence has properties akin to a random flow, more similar to another turbulent regime called ultra-quantum turbulence which has been observed in superfluid helium. In the second problem, we consider the superfluid flow of liquid helium over the surface (profiled by atom force microscopy) of a wire used to experimentally generate turbulence. Numerical simulations reveal that the sharpest features in the surface induce vortex nucleation both intrinsically (due to the raised local fluid velocity) and extrinsically (due to their role as pinning sites of vortex lines aligned with the flow which spool more vortex lines). Vortex interactions and reconnections contribute to form a well-defined, dense, turbulent layer of vortices with a non-classical average velocity profile and which continually sheds small vortex rings into the bulk. We characterise this behaviour for various imposed flows.
Helicity, topology, and Kelvin waves in reconnecting quantum knots

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Helicity is a topological invariant that measures the linkage and knottedness of lines, tubes, and ribbons. As such, it has found myriads of applications in astrophysics, fluid dynamics, atmospheric sciences, and biology. In quantum flows, where topology-changing reconnection events are a staple, helicity appears as a key quantity to study. However, the usual definition of helicity is not well posed in quantum vortices, and its computation based on counting links and crossings of centerline vorticity can be downright impossible to apply in complex and turbulent scenarios. We present a definition of helicity which overcomes these problems and which gives the expected result in the large-scale limit. With it, we show that certain reconnection events can excite Kelvin waves and other complex motions of the centerline vorticity, which slowly deplete helicity as they interact nonlinearly, thus linking the theory of vortex knots with observations of quantum fluids. This process also results in the depletion of helicity in a fully turbulent quantum flow, in a way reminiscent of the decay of helicity in classical fluids.
Vortex wave turbulence in superfluid 3He-B

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Quantum turbulence interlinks in a complicated manner (i) energy cascades of different physical nature, (ii) vortex reconnections, (iii) microscopic dissipation mechanisms. We hope to gain better understanding by disentangling the problem and studying dynamics of vortex waves in the absence of the hydrodynamic energy cascade and reconnections. In a Fermi system dissipation of vortex waves is mediated by the core-bound fermion states, which opens possibilities to connect the QT research to other fields of physics, including topological matter.

We have excited wave turbulence on an array of vortex lines in rotating superfluid 3He-B by periodically modulating the rotation velocity. After stopping the excitation we have followed evolution of the density and polarization of vortex lines using localized magnon BEC probes. At temperatures below 0.2Tc the inertial-wave energy cascade develops at length scales larger than the intervortex distance. At smaller scales we observe transition from the mutual-friction dominated damping of Kelvin waves at higher temperatures to the temperature- and friction-independent dissipation at lower temperatures. We interpret this observation as a possible experimental evidence for the Kelvin-wave cascade.

Currently we are developing MEMS oscillating devices, where a single or a few vortices can be attached to directly excite Kelvin waves and to probe the resulting dissipation. First tests of such devices in superfluid 4He at temperatures down to 15 mK will be presented.
The problem of velocity profiles in channel flows dates back to the pioneering studies of Poiseuille and Hagen [1]. Surprisingly, despite half a century of experiments since the first studies performed by Vinen [2] and current important applications of cryogenics engineering [3], the features of velocity profiles of superfluid helium flows in a channel are still not fully understood. The development of innovative low-temperature flow visualization techniques (based on micron-sized tracers [4, 5] or laser-induced fluorescence [6]) has recently renewed the interest in flow profiles and has led to important findings such as, for instance, the determination of the normal fluid velocity profile in helium II thermal counterflows [7].

In this work we perform fully-coupled numerical simulations of helium II pure superflows in a channel, with vortex-line density typical of experiments. Peculiar to our model is the computation of the back-reaction of the superfluid vortex motion on the normal fluid and the presence of solid boundaries. This numerical framework has already been employed to study helium II thermal counterflows obtaining results consistent with experimental observations [8].

We focus our investigation on the coarse-grained velocity profile of the normal fluid whose dynamical state is believed to account for the significant different features observed when comparing pure superflow to thermal counterflow [9, 10]. We show that pure superflow in helium II is associated with a large-scale circulation of the normal fluid [11] which we reckon can be detected using existing particle-tracking visualization techniques (see Fig. 1). In order to test the feasibility of such experiments, we also present preliminary results on coupled lagrangian particle dynamics.

FIG. 1. (Left): coarse-grained profiles of superfluid ($u_s$, red curve), normal fluid ($u_n$, blue curve) and counterflow ($u_{ns}$, green curve) velocities. (Right): Large-scale normal fluid circulation (in blue) in presence of a vortex tangle (in red). Red arrows show the direction of the superfluid driving velocity while grey (black) circles indicate free (trapped) tracer particles.

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Systematic measurements of the normal fluid turbulence in counterflowing superfluid helium-4

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The tracer line imaging technique has been applied to study the normal fluid turbulence in steady state thermal counterflow. This technique relies on thin lines of metastable $He^*_2$ triplet molecules generated via femtosecond-laser filed ionization, which can be visualized by laser-induced fluorescence technique. Systematic thermal counterflow measurements of the mean normal fluid velocity, turbulence intensity and 2nd order transverse structure function, have been conducted at five different temperatures 1.45 K, 1.65 K, 1.85 K, 2.0 K and 2.1 K. We show that, the mean turbulence intensity weakly depends on the velocity and increases as the temperature goes up. The form of 2nd order transverse structure function deviates from the Kolmogorov energy spectrum form as the heat flux increases.
Second sound attenuation measurements in the large-scale SHREK experiment and first images from the CryoLEM.

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In the SHREK experiment [1,2] we needed to have access to the vortex line density \( L [m/m^3] \) and therefore the average inter-vortex spacing \( \delta [m] \). To measure these quantities, we developed a new sensor using the fact that temperature in superfluid helium does not diffuse like in any other fluid, but propagates. This temperature waves, also called second sound, can be described in the context of the 2-fluid model as normal component and the superfluid component oscillating with an opposite phase \((v_n-v_s)\) maximum). Therefore the attenuation of the second sound is sensitive to the flow vorticity since the mutual friction force, that couples the motion of the superfluid and the normal fluid, is proportional to the velocity difference between the 2 components \(v_n-v_s\) and to the vorticity in the flow \(\Omega=\kappa L/2\). To measure accurately this attenuation we built an open resonant cavity composed of a second sound speaker (a copper plate heated periodically) facing a very sensitive thermometer specially designed using NbN thin film deposition techniques. The heater and sensor are 5x3mm in size with a gap of ~2mm between them.

Figure 1: Amplitude of the signal read from the NbN sensor when varying the frequency of the emitted second sound wave (2f). The different colors correspond to different flow conditions described in the legend.
The quality factor of the cavity when immersed in a quiescent superfluid liquid helium (sLHe) bath is of order 10 (see figure 1). This allows us to measure accurately the attenuation of the standing wave generated in the cavity (when forced in resonant condition), as a function of the externally imposed flow conditions (see figure 1). These preliminary results are very encouraging since one can see that the attenuation increases when the flow vorticity is expected to increase. Moreover, assuming a particular orientation for the quantum vortex lines, one can relate directly these measurements to the vortex line density \( \mathcal{L} \) and therefore to the inter-vortex spacing \( \delta = 1/\sqrt{\mathcal{L}} \):

\[
\mathcal{L} = \frac{6\pi \Delta f_0}{B\kappa} \left( \frac{a_0}{a} - 1 \right)
\]

where \( a_0 \) and \( \Delta f_0 \) are respectively the amplitude and width at mid-height of the unperturbed resonant pic (measured), \( a \) is the amplitude of the resonant pic considered, \( \kappa \) is the quantum of circulation and the mutual friction coefficient \( B \) is of order unity.

The analysis of the last three measurement campaigns will be reported. We will focus on the relation between this measurements and the energy dissipation rate \( \varepsilon \) of the quantum turbulence generated by the propellers.

We will also present the first images obtained in the newly developed CryoLEM experiment (Figure 2) in the Institut Néel. This cryostat is equipped with multiple optical accesses. Thanks to these different sets of windows it is compatible with any kind of visualization based measurements techniques (such as PIV, LPT, LDV). Moreover, the CryoLEM is placed on a 1.5m diameter spinning table in order to impose a controllable rotation rate (up to 2Hz) to the superfluid LHe flow.

References:
On the Taylor’s dissipation law for the energy flux in a decaying quasi-classical turbulence

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I would like to comment on some questionable practices when estimating the rate of energy dissipation:
- extrapolating the bulk Kolmogorov spectrum to the length scale of experimental container;
- using the energy spectrum, suitable for steady (forced) turbulence, in the case of decaying turbulence.

I would also comment on the relevance of the shape of container, boundary conditions and types of initial flow. Finally, some thoughts might be presented on the possible types of flow after a stroke of a towed grid in a cylindrical channel.
The Gross-Pitaevskii equation can be used as a quantitative model for a Bose-Einstein Condensate and qualitatively for modelling superfluid helium. I present an example of each of these systems with experimental relevance. Firstly vortex scattering via impurities within a 2d Bose-Einstein condensate, with a focus on comparison with vortex pairs scattering from a single vortex. Then also a qualitative model for a hot-wire immersed in superfluid helium. Due to the strange properties of superfluids, such as zero viscosity and quantised vortices, problems arise when using classical probes to perform measurements on them. We attempt to clarify the interpretation of the use of hot-wires in this context.
Flow visualization has played an important role in the study of quantum turbulence in superfluid helium. The visualization techniques that have been developed so far involve either particle tracers (i.e. micron-sized frozen particles) or molecular tracers (i.e. He2 excimer molecules). I will discuss the advantages and issues with these two types of visualization methods and will highlight some recent results of our visualization study of counterflow and grid turbulence in superfluid helium-4. I will also discuss our ongoing work on developing the next generation flow visualization techniques. Specifically, I will discuss: 1) how we plan to create molecular tracer-line grids in helium; and 2) our collaboration with the Nagoya University group and the Oak Ridge National Lab to create tiny He2 clouds as tracers via neutron-He3 absorption reactions in helium.
Vortex filament model in superfluid helium: From single reconnection event to counterflow turbulence

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By using the vortex filament model we first analyze a single reconnection event in superfluid helium. When two vortex rings reconnect Kelvin waves are generated and they strongly increase the mutual friction dissipation. The dissipation power takes a rather universal form which can be attributed to the decay of independent Kelvin waves whose amplitudes decay exponentially in time due to mutual friction [1]. Similarly, by analyzing the decay of root mean square curvature we are able to determine the Kelvin spectrum generated directly by the reconnection event. The spectrum is not universal but has a similar slope at small scales than the cascade predictions [2]. We also analyze how the different helicity components behave during the reconnection process [3].

Second, we present preliminary results from vortex filament simulations in cylindrical pipe geometry where a vortex tangle is formed due to thermal counterflow or due to pure superflow. These results indicate, e.g., that for thermal counterflow the vortex tangle is azimuthally polarized such that, especially at low temperatures and large drives, the superfluid velocity profile becomes a parabolic-like. For pure superflow the vortex tangle remains less polarized along the azimuthal direction and the superfluid profile remains flat.

The life of vortex knots and links: the flow of knottiness across scales

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What happens if you take a vortex loop - akin to a smoke ring in air - and tie it into a knot or a link? The possibility of such knottiness in a fluid has fascinated physicists and mathematicians ever since Kelvin’s “vortex atom” hypothesis, in which the atoms of the periodic table were hypothesized to correspond to closed vortex loops of different knot types.

More recently, helicity - a measure of knottiness in fluids and plasmas - has re-emerged in fluid dynamics because, as a conserved quantity it offers the potential for fundamental insights.

Progress in understanding its implications has been hindered by lack of accessible experimental systems and explicit models. I will tell of how to make a vortex knot and link in water (in experiment), in the wave function of a superfluid (on a computer) and of what happens thence. I will use this to talk about the fabric of helicity in classical and quantum fluids and emphasize universal aspects of how it evolves.
Probing Quantum Fluids with Nanoelectromechanical Resonators


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ABSTRACT

Quantum fluids research at low temperatures has a great demand for superconducting small-scale mechanical resonating probes that have high quality factor and could be designed for a wide range of frequencies. Microelectromechanical (MEMS) and nanoelectromechanical systems (NEMS) are ideal candidates for exploring quantum fluids as they can be manufactured reproducibly, cover the frequency range from hundreds of kilohertz up to gigahertz and usually have very low power dissipation. Despite general availability of MEMS and NEMS devices, until now there were no successful measurements of NEMS resonators in the liquid phase of $^4$He. We have immersed the doubly-clamped aluminium NEMS beams in normal and superfluid $^4$He and measured the temperature dependences of the resonance frequency and width of the fundamental mechanical mode down to 1.2 K. Our nanoelectromechanical resonators have an approximately square cross-section of 0.1 $\mu$m $\times$ 0.1 $\mu$m and lengths of 50 $\mu$m and 15 $\mu$m, with corresponding fundamental frequencies of 1.2 MHz and 8.5 MHz. The damping experienced by the resonators in superfluid $^4$He is well described by the two-fluid model of liquid helium. Successful measurements at higher temperature region in superfluid $^4$He demonstrate the technical potential to probe quantum fluids on new length scales at low temperatures, with the exciting prospect of investigating superfluid $^3$He, where the coherence length is comparable with cross-sectional dimensions of our nanoelectromechanical beams.

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Direct numerical simulations of large-scale superfluid turbulence

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We report the results of direct numerical simulations of space-homogeneous, stationary turbulence of superfluid ³He and ⁴He in the framework of the two-fluid Hall-Vinen-Bekarevich-Khalatnikov coarse-grained equations. We employ the fully periodic 3D pseudo-spectral method with resolutions 256³ and 1024³. Various statistical properties of both fluid components, including energy spectra, spectral energy balance, different correlation and structure functions, were calculated in a wide range of temperatures. These results may be used for testing and developing theoretical models of the superfluid turbulence at scales above the intervortex distance and for comparison with already available and future experimental data.
Physics of finite temperature superfluid He-4 turbulence

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I discuss the mesoscopic model of finite temperature superfluid He-4 flows. By numerically solving the governing equations, I elaborate the physics of homogeneous, isotropic superfluid turbulence, and indicate the various temporal regimes of superfluid turbulence decay.
Particle dynamics in turbulent flows of He II

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The motions of relatively small particles in two-fluid flows of He II are investigated by using the Particle Tracking Velocimetry technique. It is shown that the derived flow-induced properties - such as the velocity statistical distribution - depend on the length scale probed by the particles, for both thermally and mechanically driven flows of He II. Quantum features appear indeed at small enough length scales, smaller than the average distance between quantized vortices, while, at larger scales, a classical (viscous-like) picture emerges. Additionally, regardless of the mechanically or thermally driven nature of the large-scale flow, the tails of the small-scale particle velocity distribution display the same power-law shape, which can be related to the occurrence of vortex reconnections. It is argued that this property of quantum turbulence can be linked to the small-scale similarity observed in turbulent flows of viscous fluids. These visualization results reinforce the idea that the investigation of particle dynamics in quantum flows is not only interesting in its own right but it may also contribute to the understanding of fluid turbulence in general.

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Title: Kelvin waves, helicity and phase transitions in quantum fluid flows

Peter Megson, Itamar Shani, and Daniel Lathrop

Stemming from visualization studies in superfluid helium, we explore helicity dynamics and the phase transition to superfluidity in $^4$He. A causal relationship exists between reconnection and its emission of Kelvin waves. The superfluid flows may become increasingly helical due to this process. We use three dimensional visualization experiments to document the helical motion of quantized vortices. In addition, the creation of quantized vortices at transition has many remaining puzzles. The phase transition from a classical fluid to a quantum fluid such as superfluid $^4$He may lead to the spontaneous creation of topological defects in the form of quantum vortices. Our laboratory observations support the notion that vortices are always created at transition. We describe and contrast two distinct physical mechanisms for vortex creation through transition, including the well-known Kibble-Zurek quench mechanism and a processes that is associated with conservation of angular momentum, and show preliminary experimental results.
Kelvin-wave turbulence theory for small-scale energy transfer in quantum turbulence

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(Dated: January 26, 2017)

We present an overview of recent results regarding Kelvin-wave turbulence as a mechanism for small-scale energy transport in superfluid helium and Bose-Einstein condensates. From the first indirect observations, to the construction of a weakly nonlinear six-wave kinetic description, we outline the latest theoretical formalism using wave turbulence theory for predicting the power-law behaviour of energy exchanges between a statistical ensemble of weakly interacting Kelvin-waves on a single quantized vortex line. Furthermore, we will discuss the controversy around the locality of interaction, and explain why nonlocal interactions lead to a four-wave turbulent description. Finally, we present the most recent numerical simulations using the Biot-Savart and Gross-Pitaevskii equations that both indicate nonlocality of the six-wave process.

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We investigated the resonance of a MEMS oscillator in superfluid $^4$He. The MEMS oscillator is composed of an oscillating plate (2 x 150 x 150 $\text{m}^3$) suspended above the substrate and four serpentine springs. The response of oscillator was monitored at a fixed frequency of $\approx 20 \text{ kHz}$ while quantum turbulence was generated by a nearby tuning fork. The MEMS response was immediate and spectacular: appearance of the pronounced phase noise and phase shift. The phase of the oscillator did not return to its original value even after the liquid entered back into the quiescent state. The experiments with multiple switching between turbulent and quiescent states also produced similar behavior. The phase noise spectra reveal intriguing features in the turbulent state below about 1 Hz.
Lattice Boltzmann simulations of superfluid counterflows in a pipe

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The LB method offers a computationally efficient particle-based alternative to conventional continuum-based approaches to simulate the dynamics of He-II. Therefore, the fluid is viewed as populations of fictitious particles that collide and move along the links of a discrete lattice. This obviously refers to a kinetic description of fluid motions. In the framework of the two-fluid model, dynamics is here accounted by two sets of populations (interacting through mutual friction) associated respectively with the normal and superfluid components of He-II. The complexity of the flow emerges from the repeated application of simple rules of collision and streaming of these populations over the lattice. In analogy with the theory of gases, these rules are set to be compliant (at low frequency) with the macroscopic HVBK dynamics (through a Chapman-Enskog expansion).

The particulate nature of the lattice Boltzmann method turns out to be especially adequate to represent the heating and cooling processes, which operate on each side of the pipe, as sources and sinks of superfluid and normal-fluid particles. Under a Boussinesq-like approximation that omits temperature variations, the stirring of the counterflow then arises naturally from compressibility (or pressure) effects. This modeling, complemented with suitable solid-wall boundary conditions, results in a simple and physically-relevant numerical tool allowing us to investigate the dynamics of superfluid counterflows.

Firstly, simulations of superfluid counterflows in a pipe have highlighted enhanced entrance effects at the cooled end of the pipe, which may provide an explanation for the scatter of thresholds of the T1 instability reported during the last fifty years.

Secondly, the apparition of large-scale structures that appear on both sides of an obstacle placed in a counterflow, as originally visualized experimentally by Zhang & Van Sciver (Nature Physics 1, 36-38 (2005)), has been reproduced numerically. These simulations shed some new light on the origin of these structures.
Local and nonlocal turbulent energy transfer, energy spectra and intermittency in superfluid He

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I present recent analytical and numerical results of our study of statistics of large-scale, space-homogeneous, stationary superfluid turbulence in mechanically driven superfluid $^3$He and $^4$He. The focus is placed at the mechanisms of the energy transfer between scales and between normal and between superfluid components, on the rates of energy dissipation by viscosity and by mutual friction and on the high-order statistics of turbulent velocities, including intermittency effects.

In particular, I demonstrate that in $^3$He there are two regimes of the energy transfer between scales. At low temperatures (below about $0.4 T_c$) there exists a “local” energy cascade with the step-by-step energy transfer over scales, similar to classical hydrodynamic turbulence, but with additional energy dissipation by mutual friction. This dissipation, important only at large scales, leads to the energy spectrum $E(k) \propto k^{-3}$, predicted earlier, while at small scales the dissipation by mutual friction can be neglected and classical Kolmogorov-1941 spectrum $E(k) \propto k^{-5/3}$ is recovered. For temperatures larger than $\sim 0.4 T_c$, when mutual friction dissipation is important at all scales, we observed in DNS and confirmed analytically the scale-invariant spectrum $E(k) \propto k^{-x}$ with a (k-independent) exponent $x > 3$ that gradually increases with the temperature and reaches in our simulation the value $x \approx 9$ for $T \approx 0.7 T_c$. The origin of these spectra (for $x > 3$) is the direct energy transfer from the energy containing region at small $k$ to any given $k$. 
Boundary effects in quantum turbulence at ultra-low temperatures

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In spin-down of the B-phase of superfluid $^3$He in the zero-temperature limit, we measure the dissipation in vortex dynamics caused by the interaction between the vortex-core-bound fermions and bulk excitations. Deviations from perfect cylindrical symmetry in the flow environment cause the initial response of the vortex cluster to become turbulent [1]. The remaining high polarization of vortices along the rotation axis rises the problem of the transfer of angular momentum to container walls [2, 3]. In our experiments decoupling of the vortex array from the reference frame of the container suppresses turbulent behavior and leads to the laminar late-time dynamics. The dissipation during laminar motion is determined experimentally from the change of the precession frequency of the vortex cluster at temperatures $(0.13 - 0.22)T_c$. The precession leads to periodic modulation of the spatial distribution of the order parameter probed by the nuclear magnetic resonance, and to modulation of the Andreev-scattering properties of the cluster, probed with a quartz tuning-fork. We extract the mutual friction parameter $\alpha$ and confirm that its measured temperature and pressure dependencies agree with theoretical predictions. We also find that the zero-temperature extrapolation of $\alpha$ has pressure-independent value $\alpha(T = 0) \sim 5 \cdot 10^{-4}$[4]. We attribute the zero-temperature dissipation to a new dissipation mechanism where Kelvin waves, excited at the surfaces of the container, propagate into the bulk and lose their energy through emission of bulk quasiparticles [5].

Visualization of grid-generated turbulence in He II using PTV

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We have applied the particle tracking velocimetry (PTV) visualization technique, in addition to second sound attenuation, to study the decay of quantum turbulence in the wake of a mesh grid towed through He II. Historically, quantum turbulence generated by a towed grid is probed by measuring vortex line density in the superfluid component using second sound attenuation alone. Since tracer particles used for PTV are influenced by the normal fluid and can also become trapped on quantized vortex lines, we now have the capability to resolve the time-dependent velocity field in the wake of the towed grid, as well as to directly visualize the decorated vortex lines. This gives a more complete picture of the fluid behavior and quantized vortex dynamics in quantum turbulence decay. We give an overview of our experimental facility, which has been carefully designed to ensure reliable data; show some preliminary data from the visualization and second sound experiments; and compare the results with known grid turbulence experiments and theory.
Langevin dynamics of vortex lines and thermodynamic equilibrium of vortex tangle in the counterflowing He II

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(Dated: January 31, 2017)

The problem of the statistics of a set of chaotic vortex lines in a counterflowing superfluid helium is studied. We introduced a Langevin-type force into the equation of motion of the vortex line in presence of relative velocity $v_{\text{ns}}$. This random force is supposed to be Gaussian satisfying the fluctuation-dissipation theorem. The respective Fokker-Planck equation for probability functional $P(f_{s}\{g\})$ in the vortex loop configuration space is shown to have a solution of the form $P(f_{s}\{g\}) = N \exp(-H\{s\}/T)$, where $N$ is a normalizing factor and $H\{s\} = E\{s\} - P v_{\text{ns}}$, where $E\{s\}$ is the energy of the vortex configuration $\{s\}$, and $P$ is the Lamb impulse. Some physical consequences of this fact are discussed.
Quartz tuning forks have been used extensively to study the onset of quantum turbulence in superfluids at temperatures where normal fluid dissipation is negligible. At low excitation, in the absence of turbulence, a tuning fork can be modelled as a simple harmonic oscillator. In this regime exciting a tuning fork at multiple frequencies simultaneously yields a response only at these excitation frequencies, and is simply a superposition of the solutions for single frequencies. However, at larger excitations when the fork motion exceeds the critical threshold and the fork starts creating turbulence, non-linear forces acting on the fork create additional responses at frequencies different to the excitation frequencies. These responses, the so-called intermodulation, or mixing, products, contain information about the non-linear turbulence force. The measurement of these intermodulation products is a well-established technique in intermodulation atomic force microscopy. In this work we adapt these techniques to the study of quantum turbulence.
I report recent results of a numerical study of the evolution of a localized quantum vortex tangle -a plug- in a channel counterflow of superfluid $^4$He. The unrestricted evolution of the turbulent plug in the channel was considered starting with its creation from few individual loops under counterflow conditions, followed by the decay at the same temperature until just few backbone vortices remained. The simulations were performed using Vortex Filament method with full Biot-Savart description of the vortex line velocity at three temperatures and a number of counterflow velocities. Unlike the unbounded homogeneous vortex tangles, the turbulent plugs in the channel become more anisotropic as they decay. Various statistical properties of the turbulent plug as well as the relative importance of different mechanisms affecting the local vortex line density are discussed.
Density of Vortex Lines and Superfluid Turbulence in Channel Flows

Itamar Proaccia
The Weizmann Institute of Science, Rehovot 76100 Israel

The proper way how to take into account the existence of vortex lines in superfluid turbulence is still under debate. In this talk I will review our approach to channel flow and the resulting proposed equations of motion. The analysis is backed up by computer simulations which will be described as well.
NUMERICAL INVESTIGATION OF VORTEX DYNAMICS IN A NON-LOCAL MODEL OF SUPERFLUID

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Quantum vortices are the key dynamical ingredients to the establishment of the regime of superfluid turbulence [1]. In a microscopic approach, they are commonly described by the Gross-Pitaevskii (GP) equation, which gives the dynamics of the order parameter $\Psi$ of the superfluid under a two-body local interaction (i.e. a delta-function pseudopotential) [2]. This approach allows for the description of essential phenomena such as vortex reconnection [3]. However, a local pseudopotential model does not account for the observed dispersion relation of superfluid Helium typically used in experimental investigations [4], which is marked by the presence of a roton minimum [5]. Furthermore, by neglecting density variations over the interaction range, this model fails to give a precise description of the vortex core.

This study investigates the effects of a non-local pseudopotential model on the internal structure of quantum vortices and revisits the phenomenon of vortex reconnection. To do so, we simulate a generalization of the GP equation [6] which includes a non-local interaction able to reproduce the observed roton minimum, and reads:

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \Delta \Psi + \left(\theta_a \ast |\Psi|^2\right) \Psi,$$

where $m$ and $a$ are respectively the mass and characteristic size of a Helium atom, $\ast$ the convolution product and $\theta_a$ a typical interaction pseudopotential over $a$. Equation 1 is integrated in a periodic box using a standard pseudo-spectral method with dealiasing. We presently focus on a particular initial condition consisting of two orthogonal vortices, and study their reconnection.

![Visualization of the superfluid density at the initial condition (left), during reconnection (middle) and after reconnection (right). Low densities are plotted in red and correspond to vortex cores. High densities that are generated during reconnection are plotted in green. Bulk fluid is transparent.](image)

The superfluid density $\rho = |\Psi|^2$ is represented on Fig. 1 at three different times. We observe the emergence of small scales of characteristic size $a$ related to the non local nature of the interaction of Eq. 1. We propose then to study and quantify various aspects of the reconnection, including (i) the time evolution of the kinetic and potential energy of the ensemble of the two vortices, (ii) the emergence of the small scales, i.e. the so-called rotons and (iii) the nature of the perturbations that propagate along the vortices using tracking methods [7], and elaborate whether those perturbations can be assimilated to Kelvin waves or not. We finally focus on more complex initial conditions made up of a vortex network and compare the obtained fluctuations with those obtained in classical fluid turbulence.

References

We carried a systematic search and investigation of coherent structures in highly turbulent He-II. Measurements were carried for superfluid faction of 0%, 19% and 80%. The specificities of the SHREK experiment were used to generated ultra high Reynolds numbers, exceeding $Re= 5.5 \times 10^7$ in a Von Karman configuration, and to track vortices. We found evidence for coherent superfluid vortex bundles. Their mean density, strength, spectral and spatial distribution are compared to those of vorticity filaments in classical turbulence.
Motion of Electron Bubbles along Vortices in Superfluid Helium-4

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Using a Gross-Pitaevskii model of a superfluid with suitably tuned parameters to provide the correct ratio of the radius of an electron bubble with respect to the healing length in superfluid Helium-4, we model the dynamics of the negative ion moving under the influence of an applied electric field. Full 3D simulations are performed to study the complex spatio-temporal dynamics. The motion of the bubble both within the bulk and for a bubble trapped on a quantised vortex is considered separately. Our numerical simulations reveal the dynamical mechanisms that determine the limiting velocity of these ions. For an electron bubble moving along a vortex, we put forward a theory in order to explain the recently measured electron mobilities at very low temperatures.
We report recent investigations into the transition to turbulence in superfluid 4He, realized experimentally by measuring the drag forces acting on two types of oscillating bodies. First, custom-made quartz tuning forks with fundamental resonances at 6.5 kHz and 55.5 kHz, were investigated in the temperature range 10 mK to 2.17 K. In pure superfluid in the zero temperature limit, three distinct critical velocities were observed with both tuning forks. We discuss the significance of all critical velocities and associate the newly found third critical velocity with the development of large vertical structures in the flow, which thus starts to mimic turbulence in classical fluids. Second, the damping of a torsionally oscillating disc in 4He in the two-fluid regime has been analyzed using modern experimental techniques. Three different damping regimes are observed, and the results are compared to the pioneering work of Donnelly and Hollis-Hallett, as well as to the data obtained with tuning forks. Our main aim is to contribute towards a unified picture of oscillatory flow instabilities in 4He, as well as towards a better understanding of the conditions, under which quantum turbulence in oscillatory flow may mimic its classical counterpart.
Regimes of quantum turbulence without an energy cascade

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Experiments and numerical simulations of turbulent $^4$He and $^3$He-B have established that, at hydrodynamic length scales larger than the average distance between quantum vortices, the energy spectrum obeys the same 5/3 Kolmogorov law which is observed in the homogeneous isotropic turbulence of ordinary fluids. The importance of the 5/3 law is that it points to the existence of a Richardson energy cascade from large eddies to small eddies. However, there is also evidence of quantum turbulent regimes without Kolmogorov scaling. The spectral nature of these regimes is very different: the largest eddies are weak, most of the energy is contained in the intermediate scales, and the large wavenumber range has the $k^{-1}$ dependence of isolated vortex lines. Such features suggest a tangle of randomly oriented vortex lines whose velocity fields tend to cancel each other out. This second form of turbulence, named ‘Vinen’ or ‘ultraquantum’ turbulence to distinguish it from the ‘Kolmogorov’ or ‘quasiclassical’ turbulence, has been identified both numerically and experimentally (in low temperature $^4$He and in $^3$He-B), and also (numerically) in high temperatures $^4$He driven by a heat current (thermal counterflow).

This raises the important questions of why, in such regimes, the Kolmogorov spectrum fails to form, what is the physical nature of turbulence without energy cascade, and whether hydrodynamical models can account for the unusual behaviour of turbulent superfluid helium. We describe simple physical mechanisms which prevent the formation of Kolmogorov scaling in the thermal counterflow, and analyze the conditions necessary for emergence of quasiclassical regime in quantum turbulence generated by injection of vortex rings at low temperatures. We conclude that the regimes of quantum turbulence which have been observed at both high and low temperatures and which are characterized by the spectral nature in which most of the energy is contained at the intermediate scales, and the fully developed energy cascade is absent, can be understood on the ground of simple large-scale quasiclassical (“hydrodynamical”) considerations.
Reconnection is a fundamental event in many areas of science, from the interaction of vortices in classical and quantum fluids, and magnetic flux tubes in magnetohydrodynamics and plasma physics, to recombination in polymer physics and DNA biology. By using fundamental results in topological fluid mechanics, the helicity of a flux tube can be calculated in terms of writhe and twist contributions. We prove that the writhe is conserved under anti-parallel reconnection. Hence, for a pair of interacting flux tubes of equal flux, if the twist of the reconnected tube is the sum of the original twists of the interacting tubes, then helicity is conserved during reconnection. Thus, any deviation from helicity conservation is entirely due to the intrinsic twist inserted or deleted locally at the reconnection site. This result has important implications for helicity and energy considerations in various physical contexts.

We will discuss the mathematical similarities between reconnection events in biology and physics, and the relationship between iterated reconnection and curve topology. In particular, the minimal reconnection cascade from (2, 2k+1) torus knots to (2,2k) torus links to the unlink of two unknotted circles observed in DNA site-specific recombination is also observed in fluid vortex reconnections. We will also discuss helicity and reconnection in a tangle of confined vortex circles in a superfluid.

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References
We report measurements of the mass flow rate of superfluid 4He through single nanopipes with diameters that range from 20 nm to 200 nm. The smallest nanopipes are made by etching a single ion track in a polymer or mica, while the larger ones are made from drawn glass capillaries. The flow is driven by a pressure gradient, with one end of the nanopipe connected to a reservoir that can be pressurized up to 30 atm, with the other end in vacuum. The flows, which are in the range of a few nanograms per second, are measured with a mass spectrometer. The flows we observe are quite different from those in macroscopic pipes. In the smallest tubes the critical flow velocity is strongly dependent on temperature and can exceed 10 m/sec at T=0.5K. As a function of pressure drop, the flows exhibit two regimes. For low pressure drops, the flow rate is a rapidly increasing function of P. At high pressure drop, the flow becomes independent of the pressure drop. It is remarkable that the superflows can sustain a pressure drop of more than 20 atm over a length of a few millimeters. These large pressure gradients are presumably due to the generation and transport of vorticity in the nanopipe, but conventional models of these processes cannot account for our observations.
Imaging Diminutive Jets of Superfluid Helium

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Recent x-ray scattering experiments revealed the instantaneous positions and shapes of quantum vortices in freely rotating droplets produced upon the breakup of free helium jets in vacuum. While the exact origins of vorticity remain to be understood, it is conceivable that vortices are generated during the turbulent free-jet expansion of pressurized liquid helium through a 5 µm diameter nozzle. Here, we report an extension of our imaging experiments to optical microscopy of the jet close to the nozzle. Although, optical microscopy cannot resolve quantum vortices in a droplet, the sizes and shapes of the droplets with diameters ranging from 500 nm to 8 µm and aspect ratios close to 2 are observed. We also present different regimes of the jet breakup at varying nozzle temperatures and stagnation pressures of helium. These experiments will contribute to a better understanding of the formation mechanism and rotation of helium droplets, as well as the origins of their shape oscillations and quantum vortices.
Two-dimensional imaging of turbulence using quasiparticles in superfluid 3He-B

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We present studies of a vortex tangle created by a vibrating wire in superfluid 3He-B. Measurements were carried at low temperatures where the normal component of the superfluid comprises ballistic quasiparticles. Fermionic excitations in addition to the normal scattering can undergo Andreev reflection, which underpins non-invasive imaging of structures present in the superfluid such as quantum vortices. In ballistic regime, vortices have a large cross-section for Andreev reflection of quasiparticles, and can be imaged via the damping of small nearby mechanical oscillators. We have built and characterized two elementary blocks required for two-dimensional imaging, a quasiparticle-source and two-dimensional detector. We utilized a black-body radiator (BBR) as a source of quasiparticles and constructed a 5x5 two-dimensional camera using quartz tuning forks. The vibrating wire resonator placed between the BBR and the camera was used to produce a quantum turbulence. We took 'images' of an excitation beam emitted by the quasiparticle source and of quantum turbulence created by the wire.
Fully coupled dynamics of the two-fluid model in thermal counterflow in a square channel

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Since the proposal of the two-fluid model by Tisza and Landau, the model has made lots of contribution for revealing various phenomena of superfluid $^4$He. Numerical simulation of the vortex filament model (VFM) is based on the two-fluid model too, working well for studying thermal counterflow. However, most works using the VFM have supposed that the normal fluid was stationary to be laminar, addressing only the dynamics of quantized vortices.

The recent visualization experiments changed the situation drastically. By using the metastable triplet-state $\text{He}_2^*$ molecules, Marakov et al. observed the profile of the normal fluid in thermal counterflow in a square channel; the profile was observed to change from a laminar Poiseuille via a laminar tail-flattend to turbulent as the heat flux increased [1]. This transition should come from the kickback from a vortex tangle to the normal fluid through mutual friction. These observations invite us to address two novel kinds of studies. One is the channel or duct flow. Since the pioneering works by Schwarz most numerical studies of the VFM were performed for a homogeneous system, but recently appear several works studying channel or duct flows [2]. The other is the coupled dynamics of the two fluids. A few number of works appear recently [3].

In this work we study numerically the coupled dynamics of the two fluids in thermal counterflow in a square channel. The dynamics of the quantized vortices are addressed by the VFM using the full Biot-Savart calculation, and the dynamics of the normal fluid flow is described by the Navier-Stokes equation. And they are coupled through the mutual friction. A typical result is shown in the figure, which shows simultaneously the profile of the normal fluid flow and the distribution of a vortex tangle. The computational box is $1\text{mm}^3$, $T=1.9K$ and $v_n=0.8\text{cm/s}$. The normal fluid and the vortex tangle are strongly coupled to make characteristic inhomogeneous dynamics. We discuss the detail of the formulation and the results.
Small particle motions in superfluid HeII: its size effect on particle velocity and acceleration

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Small tracer particles in HeII are visualized and their motions are analyzed. Lagrangian statistics are computed by analyzing the visualized particle images through PTV (Particle Tracing Velocimetry) technique. Particles are made of solid hydrogen particulates from the gas phase. We studied how the particle sizes affect the statistics of particle motions, especially the particle accelerations. Probability density functions of particle acceleration are compared with that of classical fluid.
Decaying quantum turbulence in the wake of a grid towed through He-II was studied using the visualisation of the flow of the normal fluid component for several temperatures in the range 1.45 -- 2.15 K. The method of visualisation was the laser-induced fluorescence of a line of He excimer molecules. This experimental technique allows us to measure the normal fluid velocity field along a line perpendicular to the flow, with which it is possible to calculate one-dimensional energy spectra and the transverse Eulerian structure functions. The used experimental technique provides data on the flow field with sufficient accuracy to allow for calculations of the structure functions up to, typically, seventh order. Turbulence with roll-off exponent of the energy spectrum close to $-5/3$ is observed after a few seconds of the decay. At this time instant in the decay, the third order transverse structure function $S_3$ depends approximately linearly on the scale, in agreement with the classical Kolmogorov 4/5 law. In line with the extended self-similarity hypothesis, structure functions of other orders scale with $S_3$ in a power law-like fashion. The scaling exponents are found to depend on temperature, with close to K41 scaling for higher temperatures and with the strongest observed deviation from classical values in the vicinity of 1.85 K in accord with theoretical predictions of Bou"é et al.
Micrometer sized free helium jets and nano-droplets offer a unique platform for extending studies of superfluid hydrodynamics and turbulence to meso- and nano-scales. This talk will start with a review of the corresponding experimental techniques and estimates of the attainable vorticity. The droplets of 200 to 2000 nm in diameter resulting from the jet breakup in vacuum are visualized with diffusion of femtosecond x-ray pulses from a free electron laser. The angular velocities of the droplets were estimated from the centrifugal distortion and span a range of $10^5$ - $10^7 \text{ rad/s}$. For visualization of vortices, Xe atoms were added to the droplets, where they gather in cores forming nanometer-thin filaments. A newly developed phase retrieval technique enables the reconstruction of the instantaneous positions and shapes of the vortices from the diffraction images with about 20 nm resolution as depicted in Fig.1. The vorticity attainable in the nano-droplets was found to be about six orders of magnitude larger than achieved in previous experiments in the bulk. Stationary configurations of vortices are represented by triangular lattice in large (2 μm) droplets and symmetric arrangements of few vortices in smaller (500 nm) droplets. Evidence for non-stationary vortex dynamics comes from observation of asymmetric formations of vortices in some droplets. This collaborative work was performed at Linac Coherent Light Source, the free electron laser within SLAC National Accelerator Laboratory. The experiments and the full list of collaborators are reported in Refs: [1-3].

Figure 1: Image of a 600 nm diameter superfluid $^4$He droplet (blue) with six vortex filaments (red) as obtained from the x-ray diffraction pattern shown in the background [2].

Evolution of a superfluid vortex filament tangle driven by the Gross-Pitaevskii equation

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The development and decay of a turbulent vortex tangle driven by the Gross-Pitaevskii equation is studied. Using a recently developed accurate and robust tracking algorithm, all quantized vortices are extracted from the fields. The Vinen's decay law for the total vortex length with a coefficient that is in quantitative agreement with the values measured in helium II is observed. The topology of the tangle is then investigated showing that linked rings may appear during the evolution. The tracking also allows for determining the statistics of small-scale quantities of vortex lines, exhibiting large fluctuations of curvature and torsion. Finally, the temporal evolution of the Kelvin wave spectrum is obtained providing evidence of the development of a weak-wave turbulence cascade. Ongoing investigations on reconnections may also be presented.
Motion of electrons along quantized vortices in superfluid 4He

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We have measured the mobility and limiting terminal velocity of electron bubbles (negative ions) sliding along vortex lines in superfluid 4He for a broad range of temperatures (0.1 - 1 K). This allows dissipative processes at small length scales to be probed, which can include drag exerted by an excess density of excitations in the vicinity of the vortex core; the scattering and generation of vortex waves and solitons; condensation of 3He impurity atoms onto vortex cores. We have also used this technique to probe the dynamics of agitated vortex arrays and the corresponding timescales for relaxation back towards a rectilinear array, providing new insight into the decay of quantum turbulence at short length scales.
Temporal Decay of Grid Turbulence in He II in a Large Square Channel

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Turbulence temporal decay is investigated in superfluid $^4$He in a large square channel (4.6 cm x 4.6 cm square). A pulled grid is used to generate turbulence with different speeds up to 60 cm/s. A conventional second sound attenuation method (*) is used to calculate the turbulence vortex line density (L) over a temperature range from 1.5 to 2.1 K. A signal processing technique (phase locked tracking system) is used to minimize frequency shift effects caused by temperature fluctuations.

Decay of grid turbulence has been predicted by a theory stating different power laws for before and after saturation of energy containing eddies. According to the theory, L should decay as $t^{-11/10}$ (*) or $t^{-17/14}$ ($) when the length scale of energy containing eddies grows from the grid mesh size to the size of the channel. At later time, after the energy containing eddy size becomes comparable to the channel, L should follow $t^{-3/2}$ ($) .

We discuss the experimental data in this context showing evidence for $t^{-11/10}$ during part of the early time and $t^{-2}$ instead of $t^{-3/2}$ for later time. The possible explanation for the discrepancy will be discussed. Moreover, consistent bump/plateau features in between the two decay regions are presented and discussed.

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To investigate the formation of quantum turbulence in superfluid $^4$He, we have studied the emission of vortex rings from turbulence generated by a vibrating wire. The emission rate of vortex rings with a ring size of larger than 38 $\mu$m in diameter remains low until the beginning of high-rate emissions. The emission change suggests that some of the vortex lines produced by the wire combine to form a vortex tangle, until an equilibrium is established between the rate of vortex line combination with the tangle and dissociation. The formation times of equilibrium turbulence are proportional to $\varepsilon^{-1.2}$ and $\varepsilon^{-0.6}$ in the directions perpendicular and parallel to the vibrating direction of the generator, respectively, indicating the anisotropic formation of turbulence. Here $\varepsilon$ is the generation power of the turbulence. This power dependence may be associated with the characteristics of quantum turbulence with a constant energy flux.
Numerical studies of decay of thermal counterflow turbulence in superfluid $^4$He

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This work addresses the decay of thermal counterflow turbulence in superfluid $^4$He, by using numerical simulation of the vortex filament model. At large heat currents, the two-fluids are turbulent, and can affect each other in large scale. This large scale coupled turbulence shows the $t^{-3/2}$ decay, and has been studied well[1]. On the other hand, the decay at small heat currents, which may show the $t^{-1}$ decay, has never been addressed sufficiently by experiments, and there have been no reliable measurements of the decay coefficient.

Recent experiment by J. Gao, W. Guo and W. F. Vinen has investigated the decay coefficient of thermal counterflow turbulence at small heat current. However, there are a few numerical studies investigating the decay of that case[2]. To consider the experimental results, more adequate numerical data of the decay coefficient is required. Accordingly, we performed numerical studies of thermal counterflow turbulence in superfluid $^4$He. First, we investigate decay from counterflow with uniform normal flow in periodic channel. We obtain the decay coefficients at $T=1.4$ K, 1.5 K, 1.6 K, and 1.7K. The figure at the bottom shows snapshots of quantum turbulence in decay at $T=1.4$ K, which is generated in periodic counterflow. Second, we investigate decay in more realistic system, namely counterflow with Poiseuille normal flow in a channel, which has never been addressed numerically.

Measuring Single Vortex Dynamics in Superfluid Helium

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I will discuss experiments on vortices using a straight vibrating wire setup, such as was originally used to measure quantized circulation in superfluid helium. In our experiments circulation surrounds only part of the wire's length, and this vortex continues as a free vortex in the superfluid. As the free vortex moves, so does the spot where it connects to the wire; we monitor the free vortex through the behavior of this attachment point. We focus on two properties. One is the interaction of the vortex with the wall of the container, as seen by pinning events and also by the energy dissipation as the end of the vortex moves along the wall. The other is Kelvin waves along the vortex. We observe the lowest Kelvin mode for both pinned and moving vortices and are working to extend our measurements to higher modes.