Listening to quantum turbulence with second sound tweezers

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Motivation: the mesoscales of QT

Velocity spectra

Superfluid 0 %
Superfluid 86 %

Kolmogorov cascade

The local length of vortex lines
An inertial-scale indicator of small scale physics

Same total "vorticity"
Different total "vortex length"
The local length of vortex lines
An inertial-scale indicator of small scale physics

The vortex length depends on small-scale processes

• dissipation,
• reconnexion,
• Kelvin wave cascade
• ...

Experimental approach to mesoscales:
measure the local density of vortex lines.
What is second sound?

In He-II, temperature follows a wave equation

$$\frac{\partial^2 T}{\partial t^2} - c_2^2 \Delta T = 0$$

$$c_2 \approx 10 - 20 \text{m/s}$$

$n$: normal fluid component
$s$: superfluid component

First sound

Second sound

A resonant cavity for temperature waves

Usually of the cm size and imbedded in the walls of a superfluid flow (e.g. Hall & Vinen 1956).
Second sound is damped by quantum vortices

- With quantum vortices, the dispersion relation is

\[ k = \frac{\omega}{c_2} + i\alpha(T)\mathcal{L}_\perp \]

\[ \mathcal{L} \] is the density of quantum vortex lines (or « superfluid enstrophy »)

vortex tangle
Second sound tweezers designed as a non-invasive probe

Standing wave in the open cavity modelled with the Huygens-Fresnel principle

\[ G(r) = \frac{1}{|r|} e^{-ik|r|} \]

- Near field diffraction
- Advection
Second sound tweezers
The model predicts the features of the spectrum

![Graph showing features like Focalization of the wave, Inclination effect, and Destructive interferences.](image)
Second sound tweezers sensitive to both quantum vortices and velocity

Attenuation proportional to the density of quantum vortices

Ballistic advection by the flow creates an extra attenuation with phase shift
Second sound tweezers
Optimization to favor vortex or velocity selectivity

Large symmetric tweezers are used to measure the density of **quantum vortices**

Small asymmetric tweezers are used to measure the **velocity**

Vortex selectivity > 90%

Velocity selectivity > 90%
Side slide:
An alternative method to sense both vortices or velocity using the same tweezers.

Low drive vs high drive

Normalized amplitude of the standing wave

Heating power driving the resonator

Overheating

U (m/s)

T/P (a.u.)

P (W/cm²)
Three new mathematical processing methods

- bulk attenuation and velocity deflection can be distinguished in the phase-quadrature plane.

- the noise from a drifting resonant frequency can be cancelled

\[ \xi_{VLD} = \frac{1}{D} \text{asinh} \left( \frac{T_0 \cos \theta}{T(f_0)e^{-i\theta}} \sinh (\xi_0 D) \right) - \xi_0. \]
GRID TURBULENCE EXPERIMENT

TOUPIE superfluid wind-tunnel

Wind-tunnel
Φ76 mm

Grid wake:
- near field @ 10M
- porosity: 0.58

Acknowledgements to B. Chabaud
GRID TURBULENCE EXPERIMENT
Highly skewed vortex line density

superfluid fraction
81%
47%
16%

Vortex line density (« enstrophy »)

Woillez EPL (2021)
Main findings on second sound resonators

- 2\textsuperscript{nd} sound tweezers can probe **both vortices and velocity**
- **New processing methods** in the complex plane eliminate out-of-phase signal

Main findings of the grid turbulence experiment

- PDF of the vortex line density:
  - Strong asymmetry.
  - Independent of the superfluid fraction.
    - Also relevant to Navier-Stokes turbulence?

- Spectra (not shown):
  - All vortex density spectra collapse independently of the superfluid fraction.
  - The shape of the spectral master curve is unexpected (no power law)
JET EXPERIMENT
Mapping the superfluid enstrophy of a jet

In collaboration with P. Švančara and M. La Mantia

Quantum vortex density \((10^{-9} \text{ m}^{-2})\)

\[
L(r, z, P) \propto \frac{P^{3/2}}{(z - z_0)^2} \exp \left\{ -\frac{r}{\beta_L (z - z_0)} \right\}^2
\]

Švančara, Phys. Fluids (2023)
PERSPECTIVE
Joint local measurements

Joint local measurements: velocity and vortex line, gradient, ...
GRID TURBULENCE EXPERIMENT
We observe an original shape of the vortex density spectrum

Spectrum of velocity

spectrum of the superfluid enstrophy.

Woillez EPL (2021)
Experimental results
Probing the quantum enstrophy in grid turbulence

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