Visualization Study of Counterflow in Superfluid ^{4}He using Metastable Helium Molecules

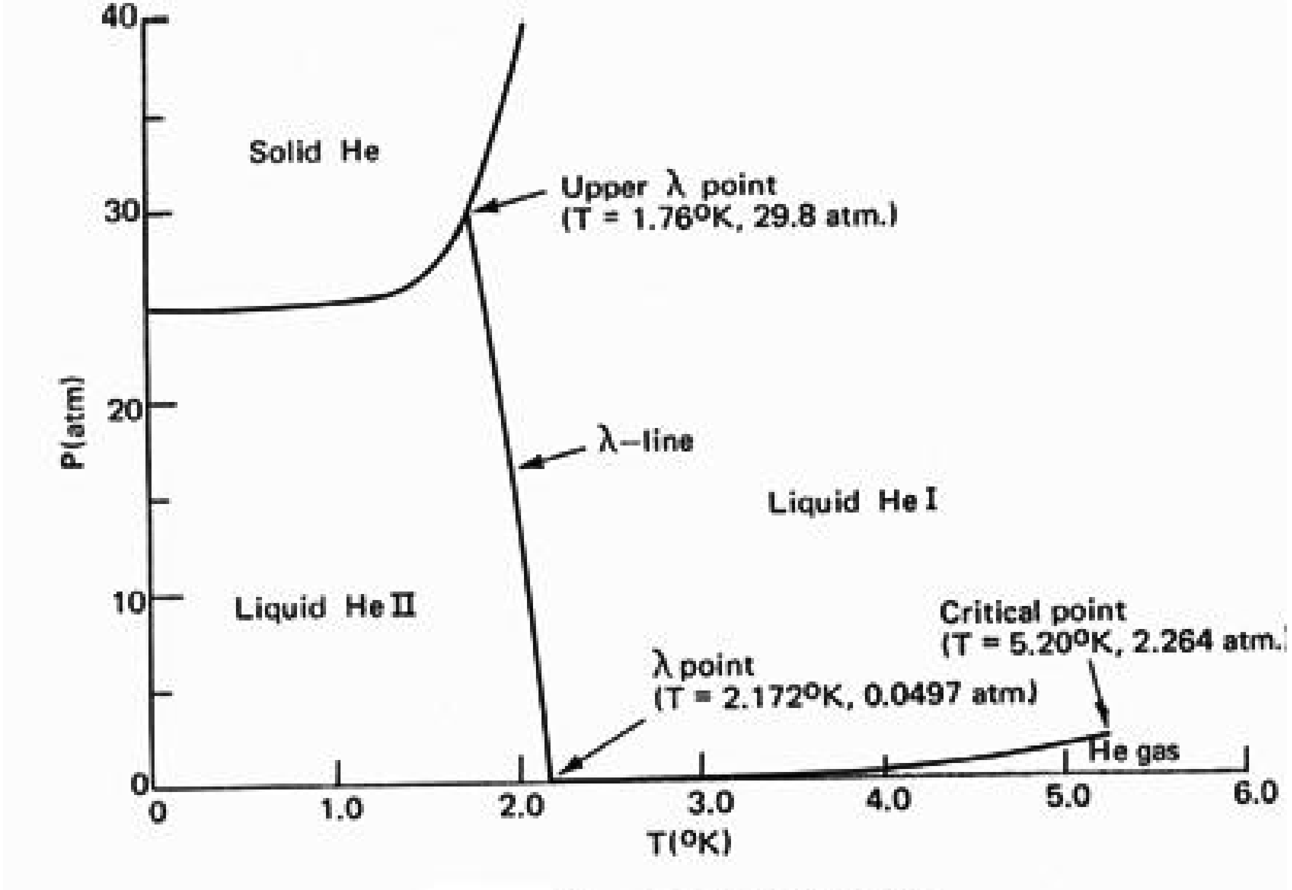
W. Guo, S.B. Cahn, J.A. Nikkel, W.F. Vinen and D.N. McKinsey

Speaker: Xin Wen

Department of Physics and Astronomy, University of Tennessee

Oak Ridge National Laboratory

Helium



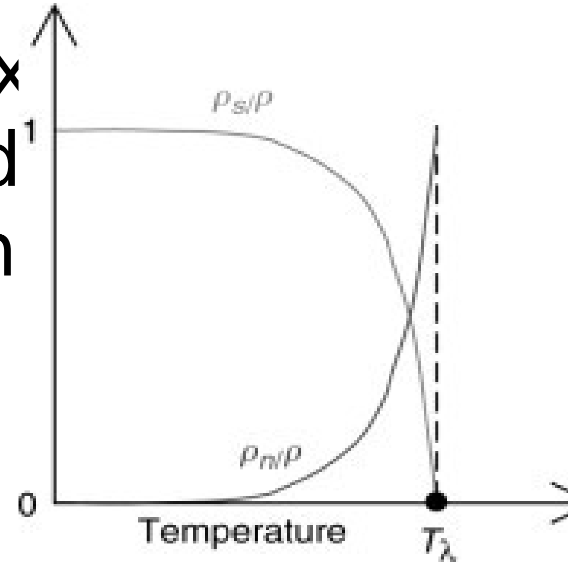
The phase diagram of He⁴.

Two Isotopes:

- ^{3}He (fermion)
- ^{4}He (boson)

Two Liquid Phases:

- He I – Normal fluid
- He II – The mix of normal fluid component an superfluid component (0 viscosity)



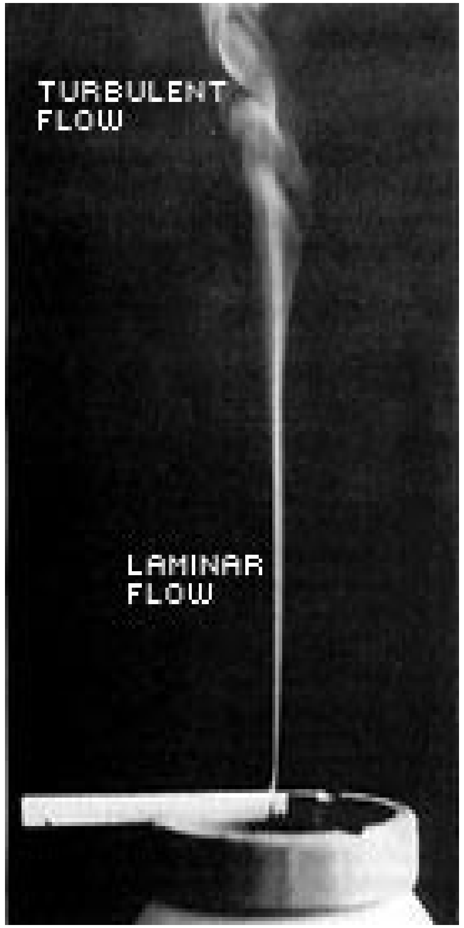
Motions of fluid

Laminar flow

- Fluid flows in parallel layers, with no disruption between the layers
- The velocity of the fluid is constant at any point in the fluid.

Turbulet flow

- Irregular flow that is characterized by chaotic changes in pressure and flow velocity.
- The velocity of this fluid is not constant at every point
- The onset of turbulent flow depends on the fluids velocity, viscosity, density, and the size of the obstacle it encounters.



Some concepts

- **Viscosity** is a measure of a fluids resistance to relative motion within the fluid
- **Reynolds number** is the ratio of inertial forces to viscous forces within a fluid

$$\mathrm{Re} = \frac{\rho u L}{\mu} = \frac{u L}{\nu}$$

- **Vortex** is a region in a fluid in which the flow revolves around an axis line
- Heat is transferred in superfluid ^{4}He via a process called **thermal counterflow.**

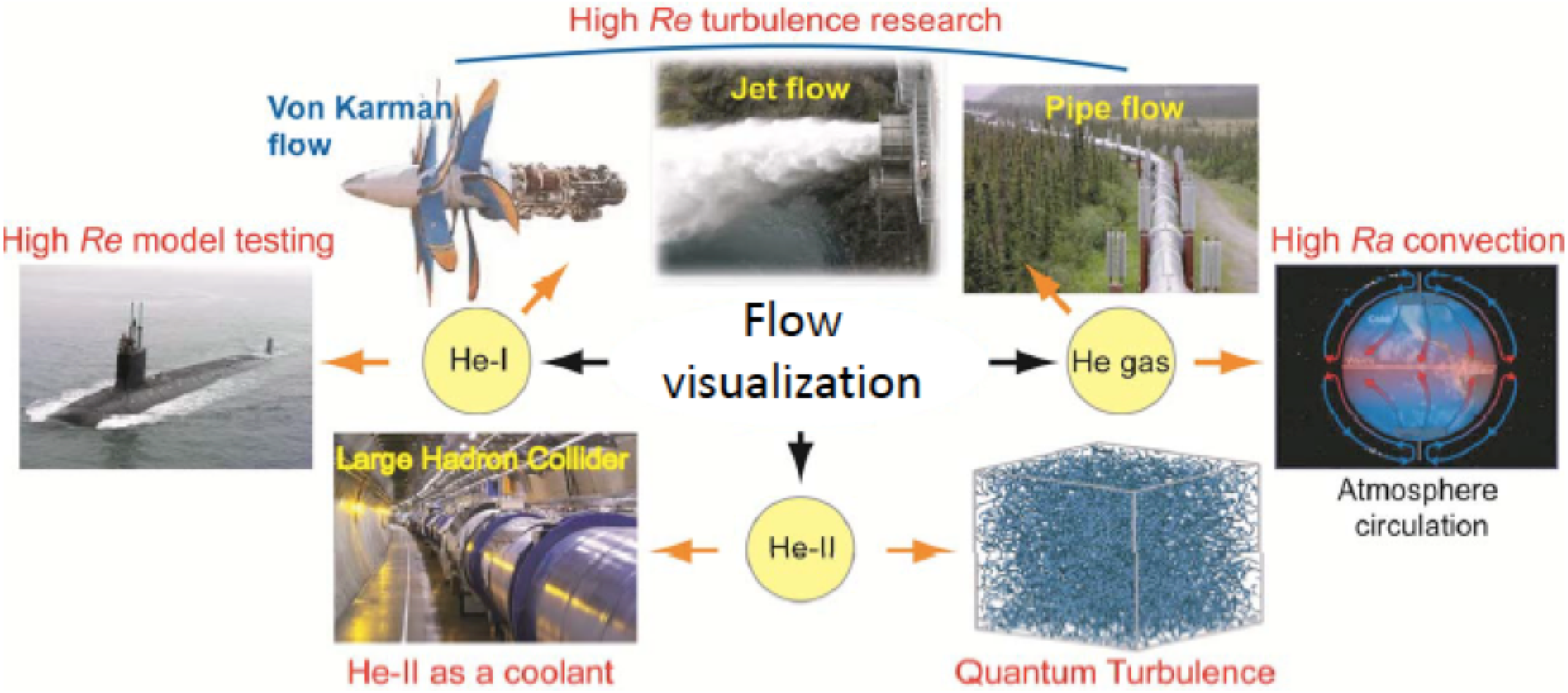
In a thermal counterflow, the **normal-fluid velocity** v_n is related to the **heat flux** q by

$$q = \rho S T v_n$$

Superfluid component in this counterflow becomes turbulent above a critical heat current. We suspect that normal-fluid component may become turbulent. [1]

[1] L. D. Landau and E. M. Lifshitz, Fluid Mechanics (Pergamon Press, Oxford, 1987).

It’s important to see the flow



Visualization of thermal counterflow

Techniques

- Particle image velocimetry [2]
- Particle tracking techniques [3]

Tracers

- Micron-sized tracer particles formed from polymer spheres or solid hydrogen (can be trapped on the quantized vortex lines)
- Cluster of electrons (repel each other, interact more strongly with quantized vortices.) [4]

[2] S.W. Van Sciver, S. Fuzier, and T. Xu, J. Low Temp. Phys.148, 225 (2007). [3] M. S. Paoletti et al., J. Phys. Soc. Jpn. 77, 111007 (2008). [4] D. D. Awschalom et al., Phys. Rev. Lett. 53, 1372 (1984).

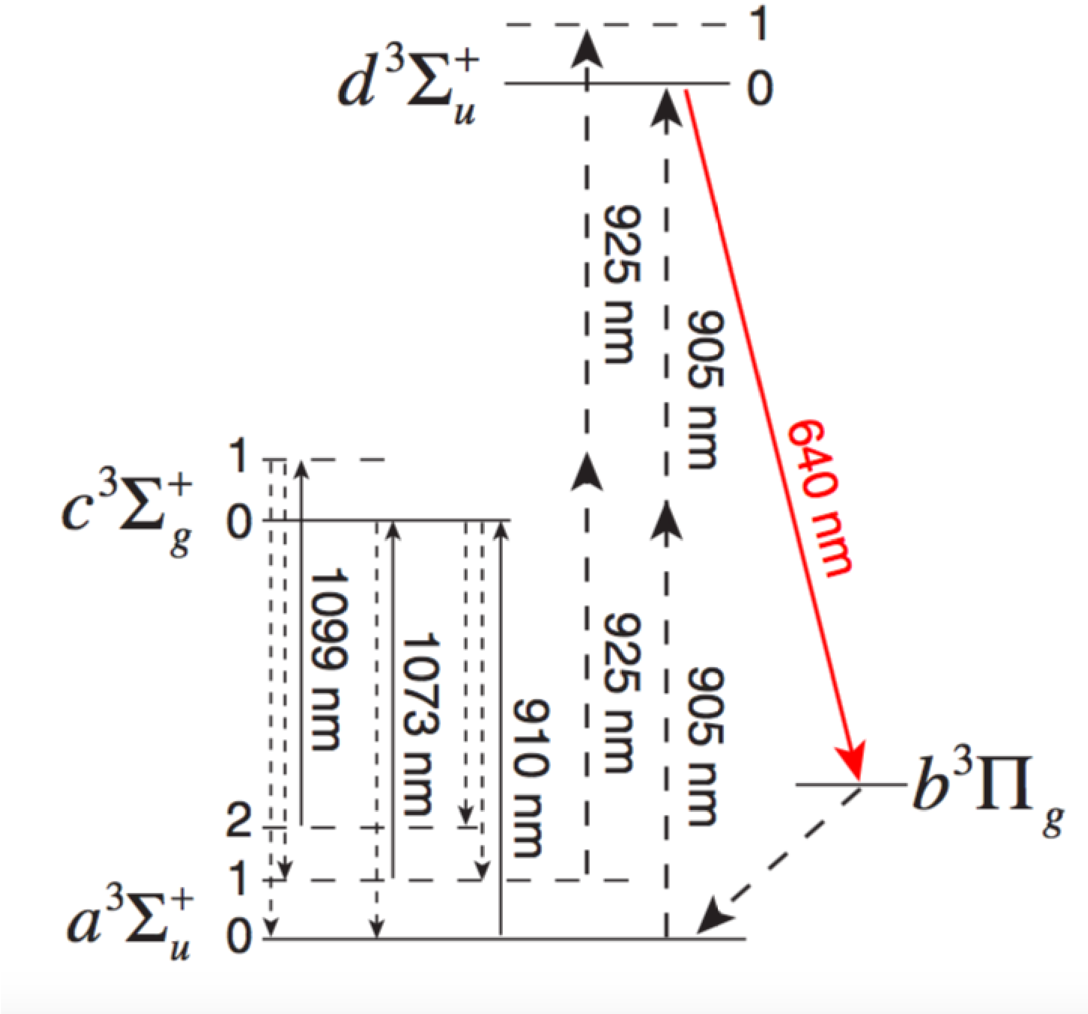
A new tracer

Metastable He_2* triplet molecules (~1 nm) with a radiative lifetime of 13 seconds in liquid helium

- Won't be trapped by vortices above 1K
- Scattering by vortices has negligible effect
- Can be imaged by **laser-induced fluorescence technique**

Technique

Molecule tagging technique to visualize the velocity profile of normal fluid



[5] W. G. Rellergert et al., Phys. Rev. Lett. 100, 025301 (2008). [6] W. Guo et al., Phys. Rev. Lett. 102, 235301 (2009). [7] W. Guo et al., J. Low Temp. Phys. 158, 346 (2010).

Conducting the experiment

Apply a negative voltage to the needles (>emission threhold ~-500V)

↓

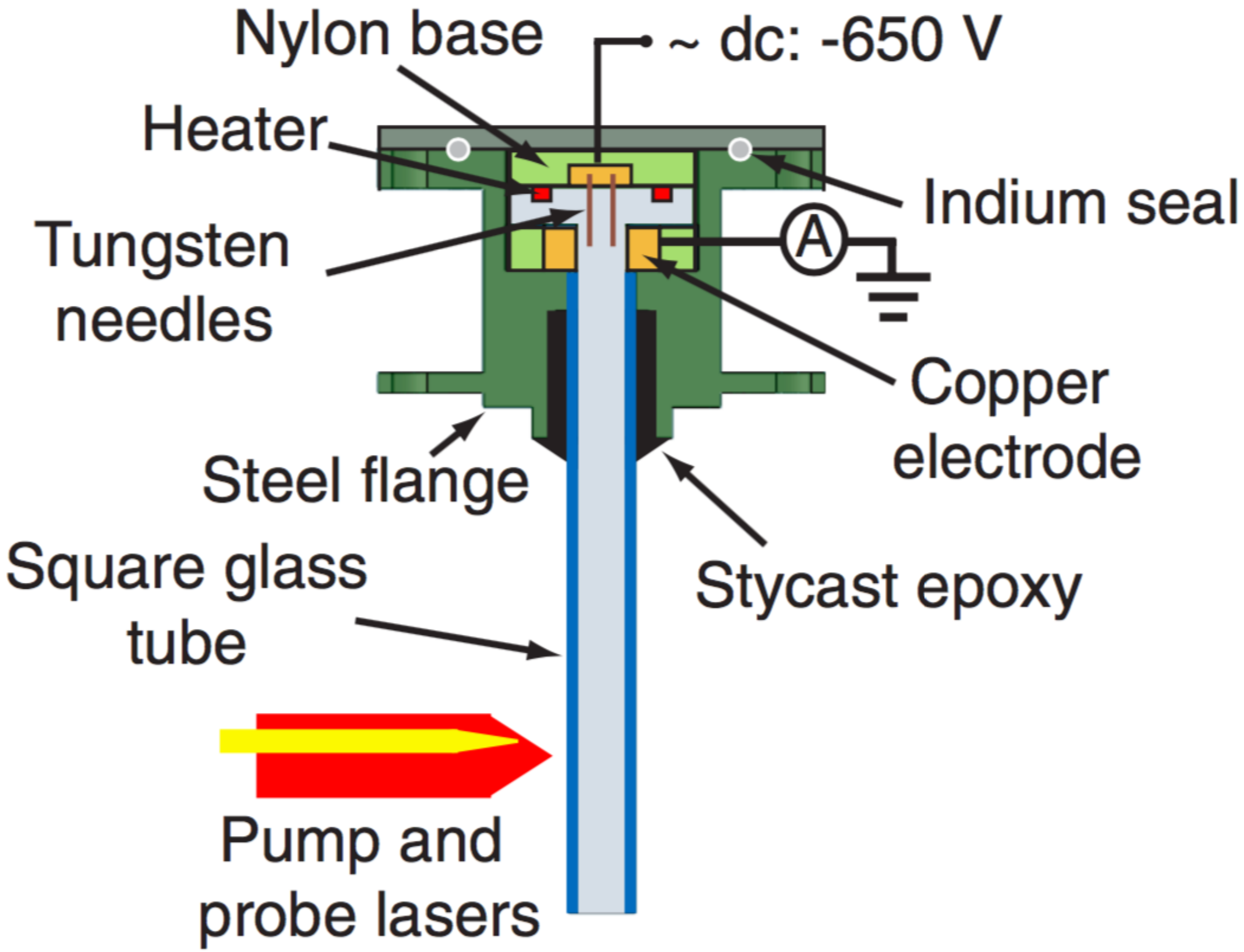
Metastable helium molecules were produced near the needle apexes

↓

Generate a counterflow in the channel with the heater

↓

Use a focused pump laser pulse (910 nm) to drive the He_2^* molecules along the beam path into the first vibrational level of the triplet ground electronic state.

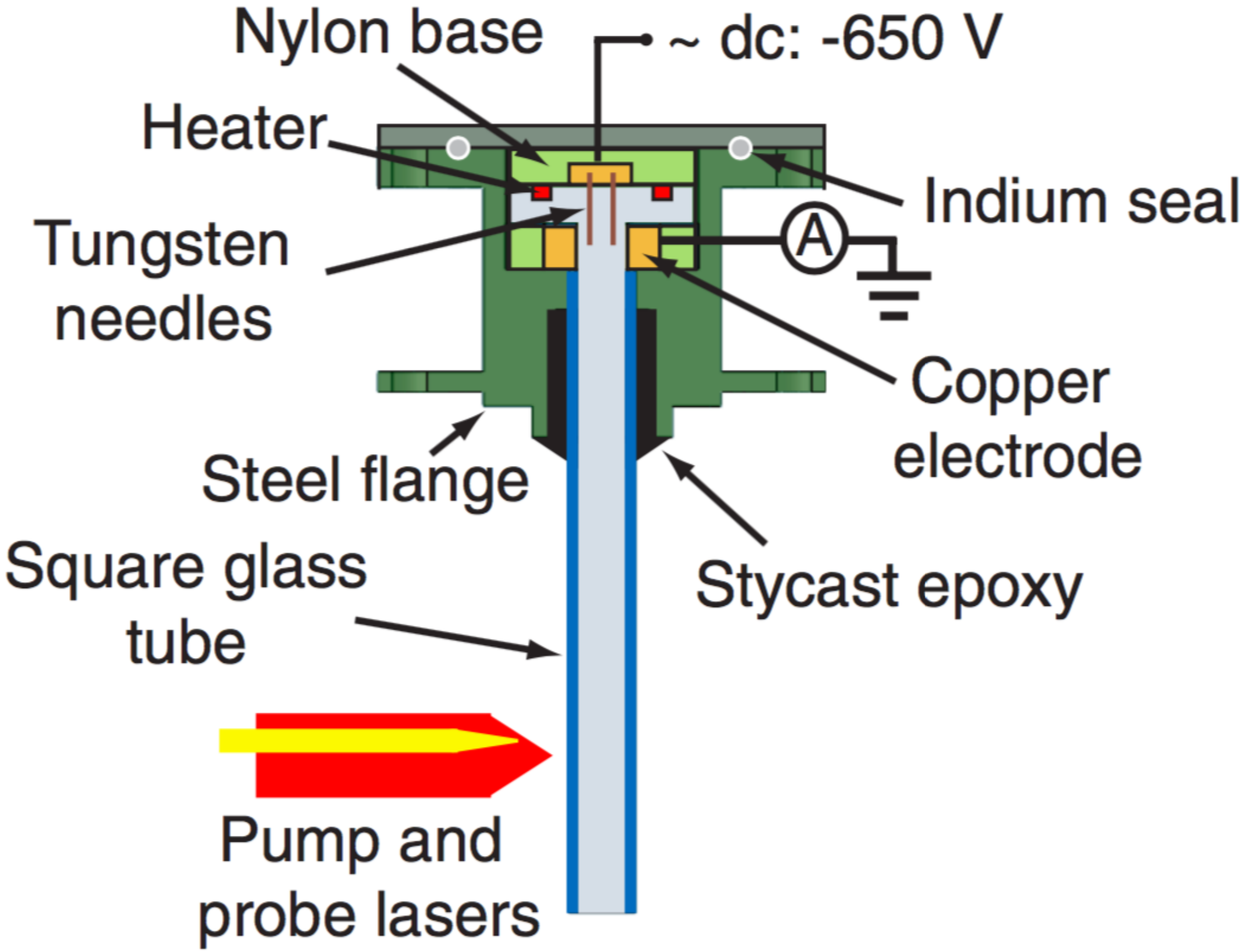


Conducting the experiment

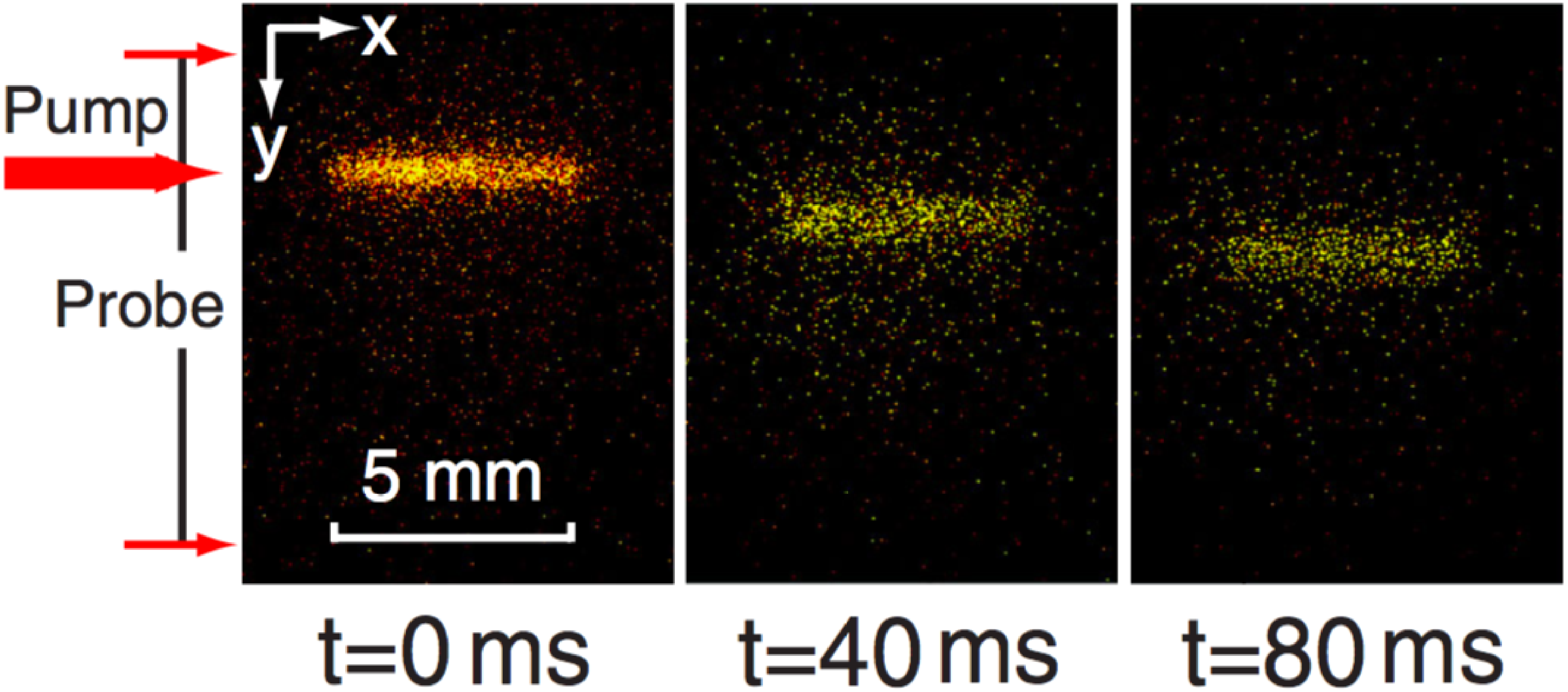
At a given delay time

Use an expanded probe laser pulse (925 nm) to image selectively the vibrationally excited line of molecules by driving them to an excited electronic state and inducing 640 nm fluorescent light

Use an intensified CCD camera to record the fluorescent light from the line of excited molecules.



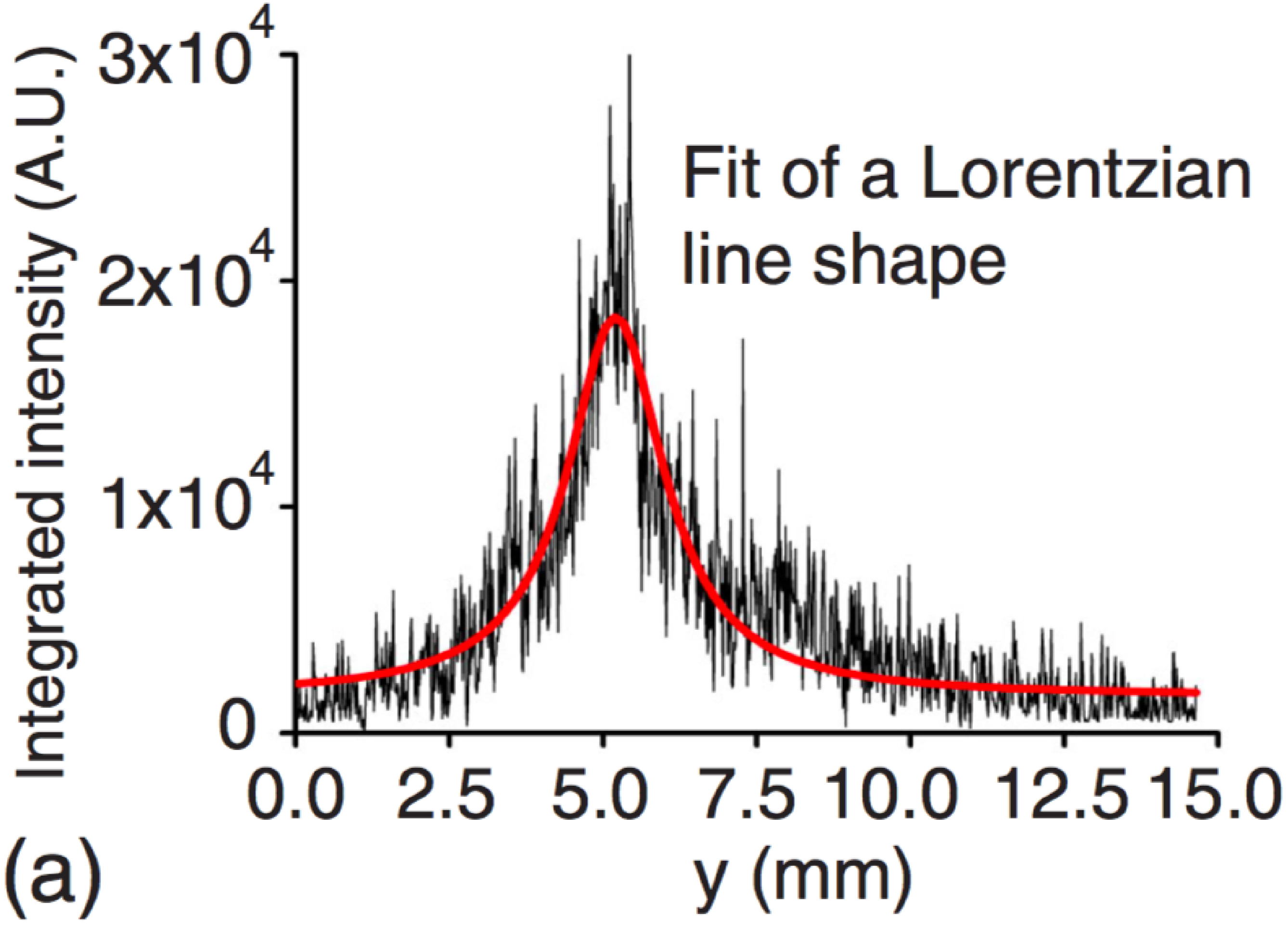
The motion of tagged molecules at a heat flux of 640 mW/cm^2



The straight line of molecules remains straight, indicating a flat normal-fluid velocity profile across the channel

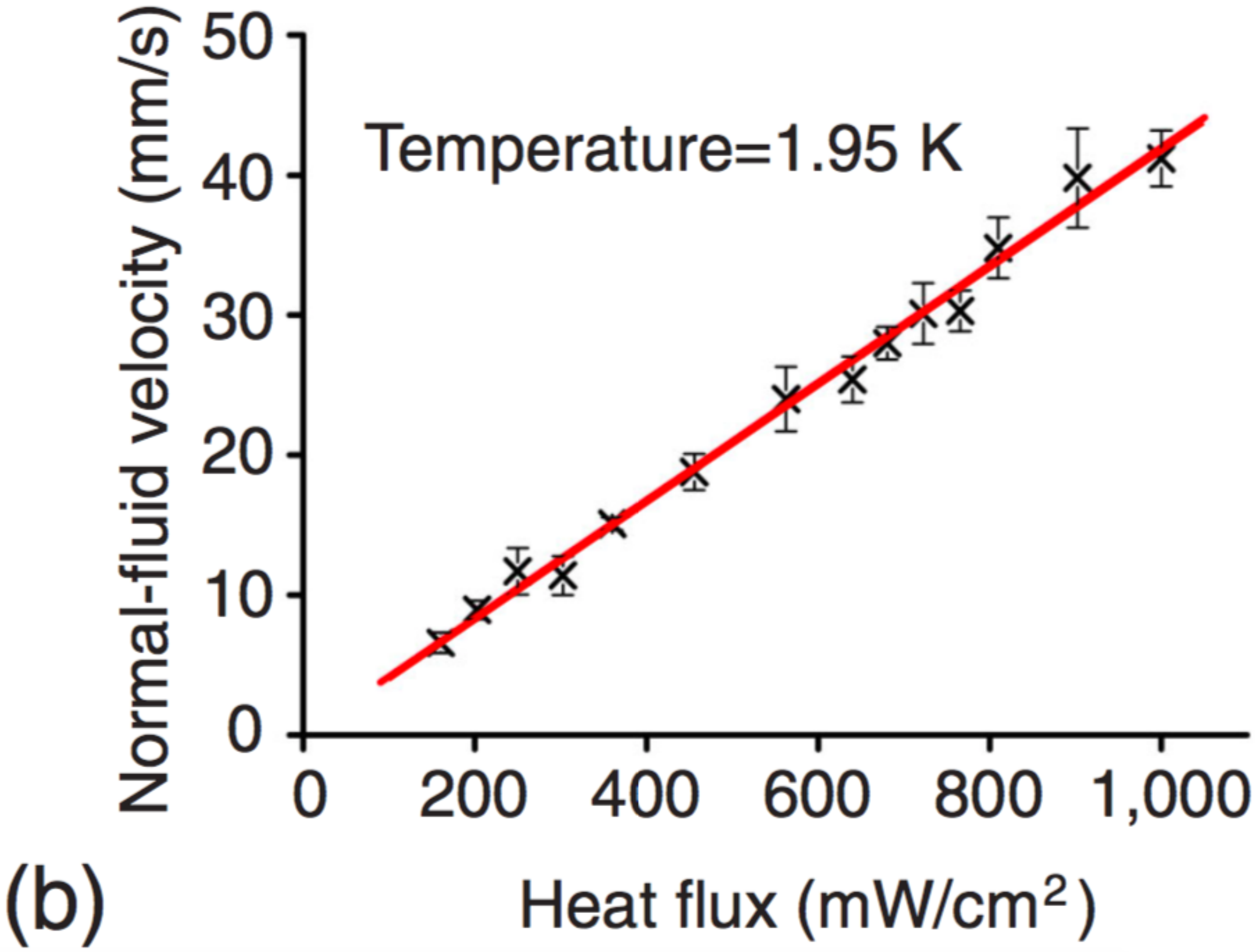
Integrate the fluorescent signal in each pixel along the x-axis for each y value

（Lorentzian fit to the data， x_0 is its maximum）

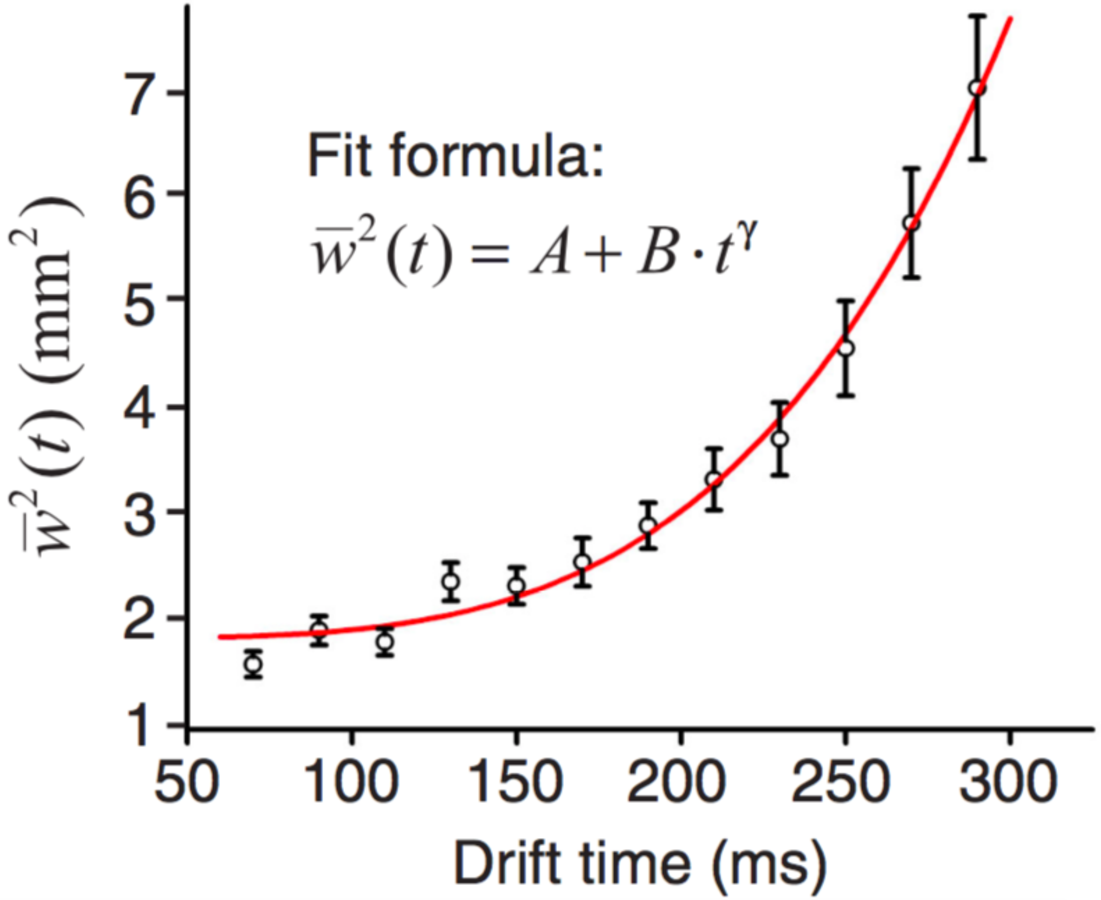


$$L(x) = \frac{1}{\pi} \frac{\frac{1}{2}\Gamma}{(x - x_0)^2 + \left(\frac{1}{2}\Gamma\right)^2},$$

The result agrees with the prediction $q = \rho S T v_n$



Broadening of the molecule line



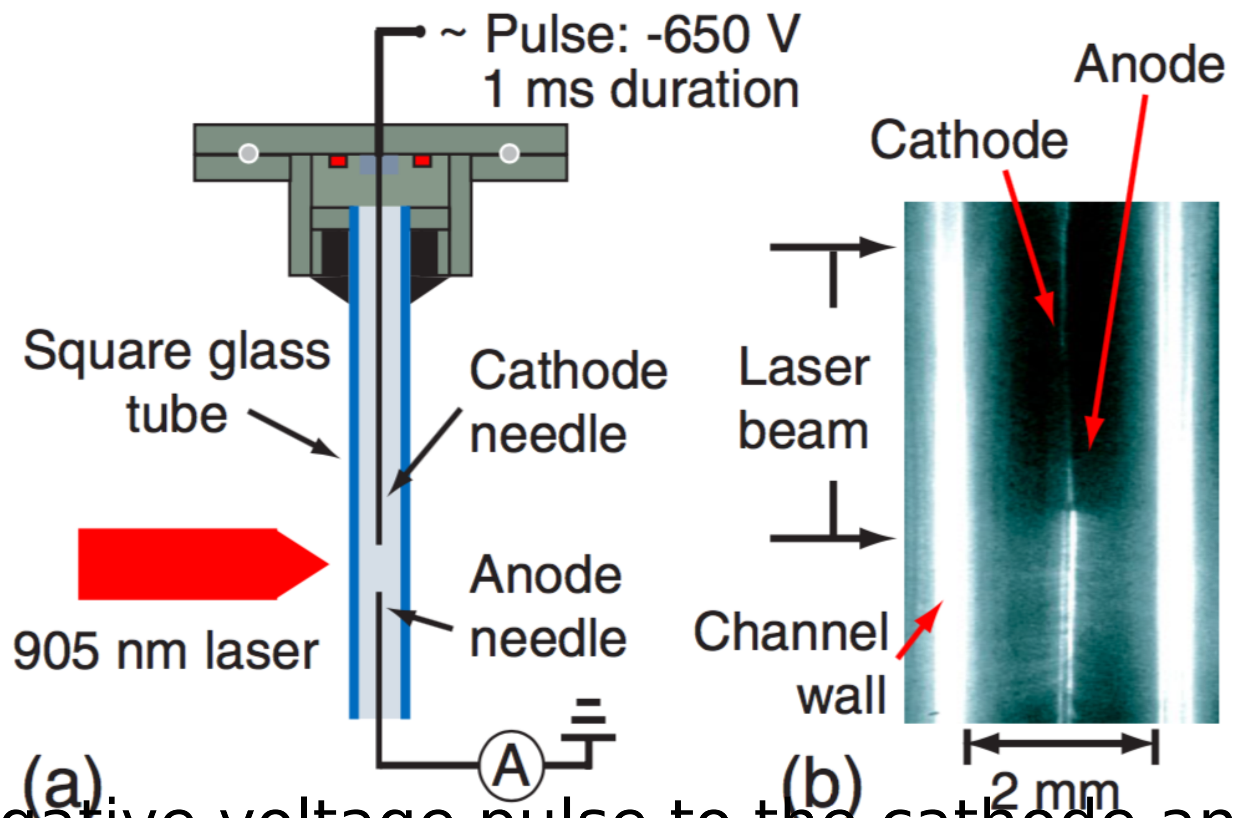
$\gamma = 4.0 \pm 0.3$

If the energy spectrum E(k) were to have the Kolmogorov form E(k) ~ $k^{-5/3}$, characteristic of classical homogeneous isotropic turbulence, then $w^2(t)$ would be proportional to t^3 for large times [8]

[8] G. K. Batchelor, Proc. Cambridge Philos. Soc. 48, 345 (1952).

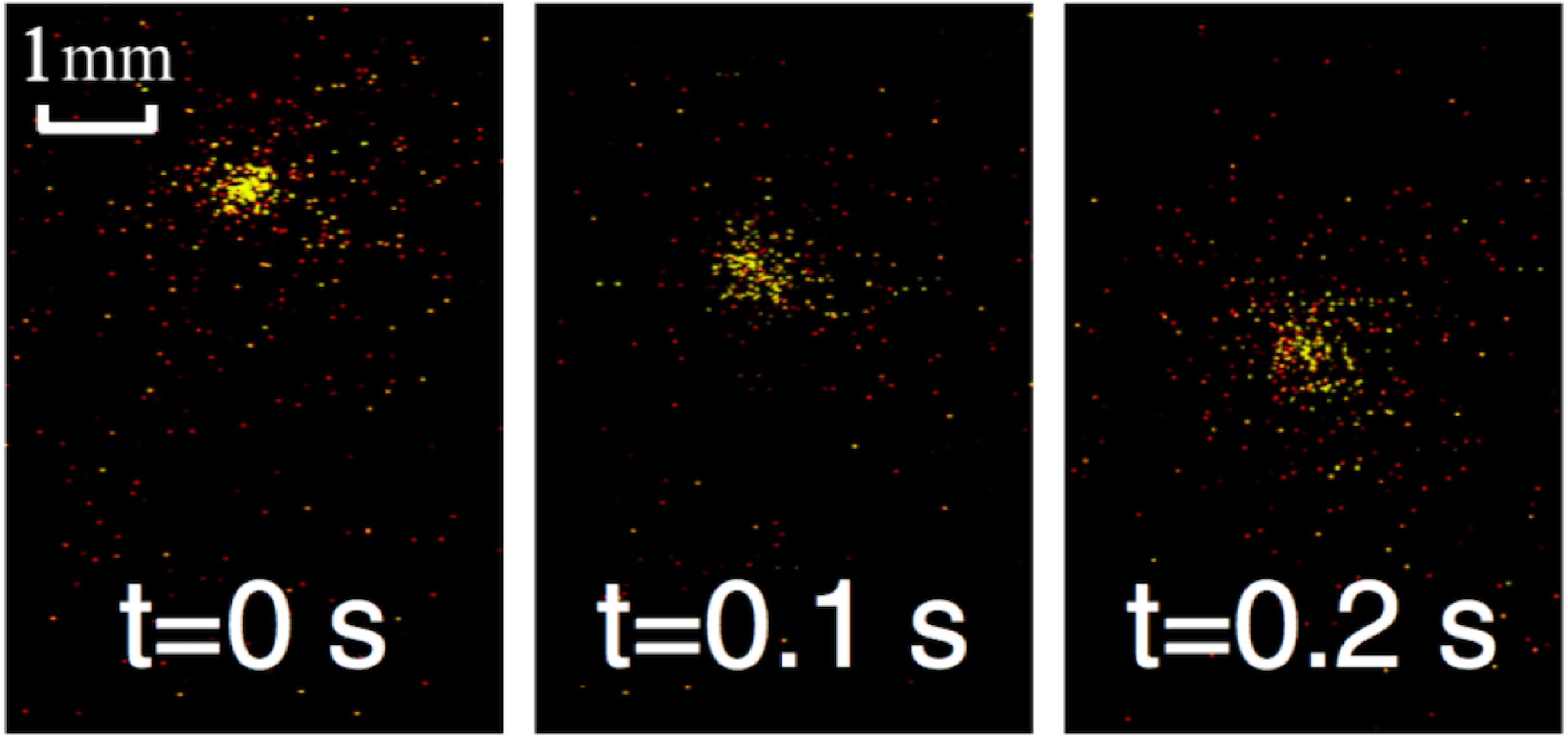
It occurs too rapidly to be explained by ordinary diffusion at experimental temperature 1.95K, so we deduce the flat velocity profile is caused by turbulent diffusion, confirming the flow of normal fluid is turbulent.

Until now, the normal-fluid velocity at large heat fluxes were studied. To measure the velocity at small heat fluxes, we use a **cluster tracking technique.**

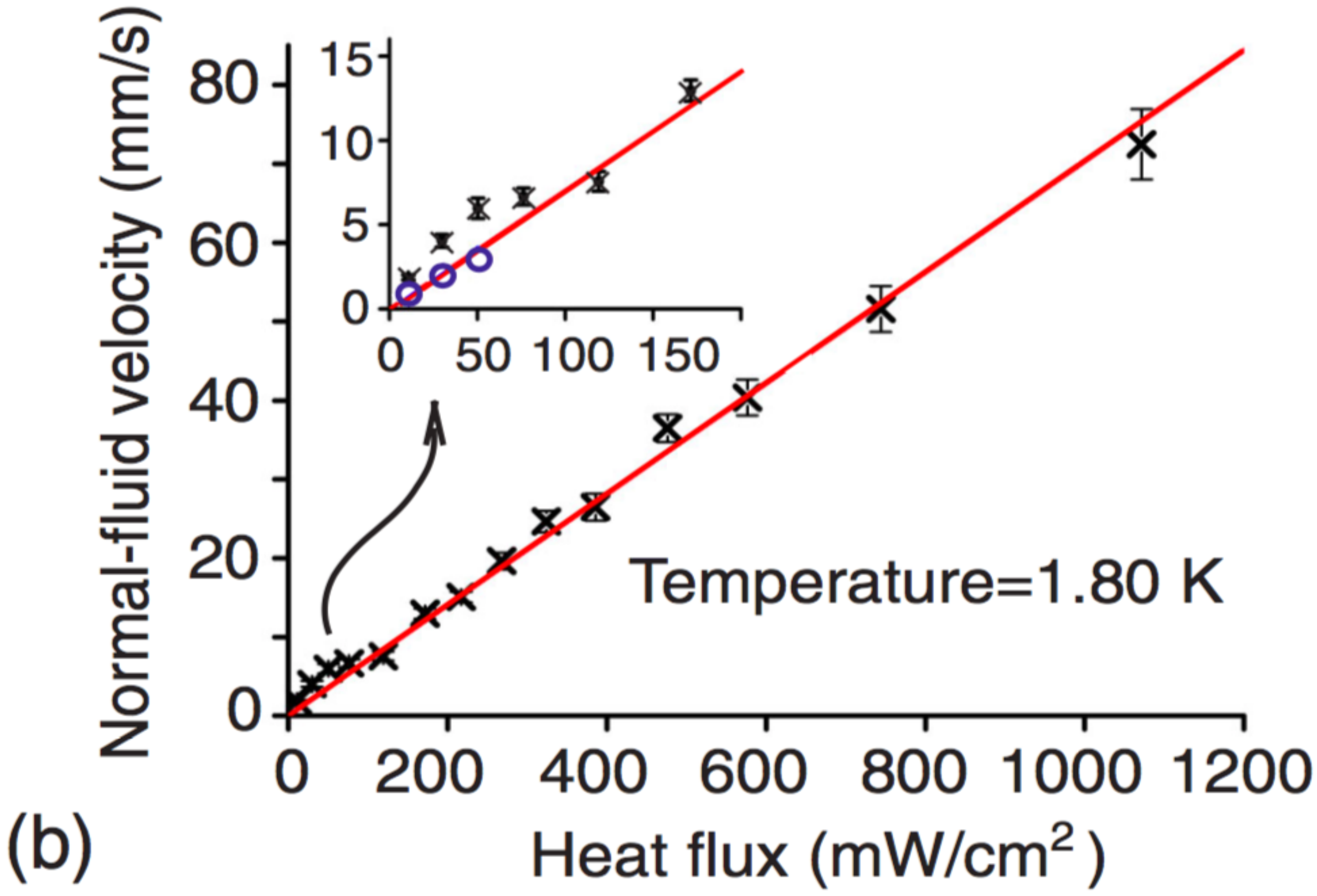


- Apply a negative voltage pulse to the cathode and a small cluster of helium molecules is created near its apex with a initial diameter of 0.5-0.8 nm
- Use a laser pulse (905 nm 500 Hz) to drive the molecules to produce fluorerscent light through a cycling transition

Images of a molecule cluster at a heat flux of 119 mW/cm^2



Fit the cluster center positons as a linear function of drift time



In small heat flux regime, both superfluid and normal fluid flows are laminar flow. The drift velocity of the cluster should be twice the velocity given by

$$q = \rho S T v_n$$

Summary

Metastable He_2^* triplet molecules can be used as tracer to visualize counterflow

The linear relationship between normal-fluid velocity v_n and heat flux q is verified

The normal-fluid component of ^4He become turbulent at high heat flux

More research needs done to explain the broadening of molecule line

Future work

- Hypothesis: Neutron beams enable measurements of turbulent flow under extreme conditions.
- Proof of principle: Demonstrate particle tracking velocimetry (PTV) using neutron beams to create metastable He molecules at Oak Ridge National Laboratory.
- Apply the technique to map turbulent flow about systematically fabricated models.
- Compare results to models of turbulent flow.

Our vision is to demonstrate an innovative capability to observe turbulent flow for applications in industry and science.

References

[1] L. D. Landau and E. M. Lifshitz, Fluid Mechanics (Pergamon Press, Oxford, 1987).
[2] W. F. Vinen, Proc. R. Soc. A 242, 493 (1957).
[3] S.W. Van Sciver, S. Fuzier, and T. Xu, J. Low Temp. Phys. 148, 225 (2007).
[4] M. S. Paoletti et al., J. Phys. Soc. Jpn. 77, 111007 (2008).
[5] D. Kivotides, Phys. Rev. B 77, 174508 (2008).
[6] M. E. Hayden et al., Phys. Rev. Lett. 93, 105302 (2004).
[7] D. N. McKinsey et al., Phys. Rev. A 59, 200 (1999).
[8] D. N. McKinsey et al., Phys. Rev. Lett. 95, 111101 (2005).
[9] W. G. Rellergert et al., Phys. Rev. Lett. 100, 025301 (2008).
[10] W. Guo et al., Phys. Rev. Lett. 102, 235301 (2009).
[11] W. Guo et al., J. Low Temp. Phys. 158, 346 (2010).
[12] D. D. Awschalom et al., Phys. Rev. Lett. 53, 1372 (1984).
[13] G. K. Batchelor, Proc. Cambridge Philos. Soc. 48, 345 (1952).
et al

Collaborators

W. Guo	M. Fitzsmmions	X. Tong	S. Bao	L. McDonald
FSU	UTK ORNL	ORNL	FSU	UTK

The End

Thank you!