Possible application of neutron in the study of quantum fluid hydrodynamics

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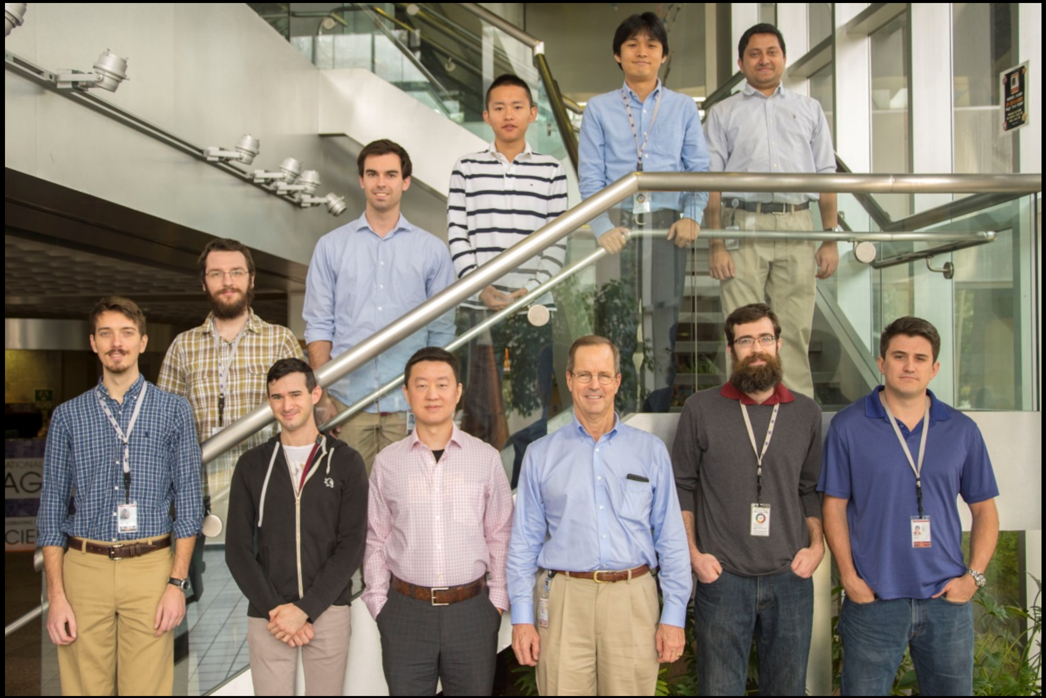
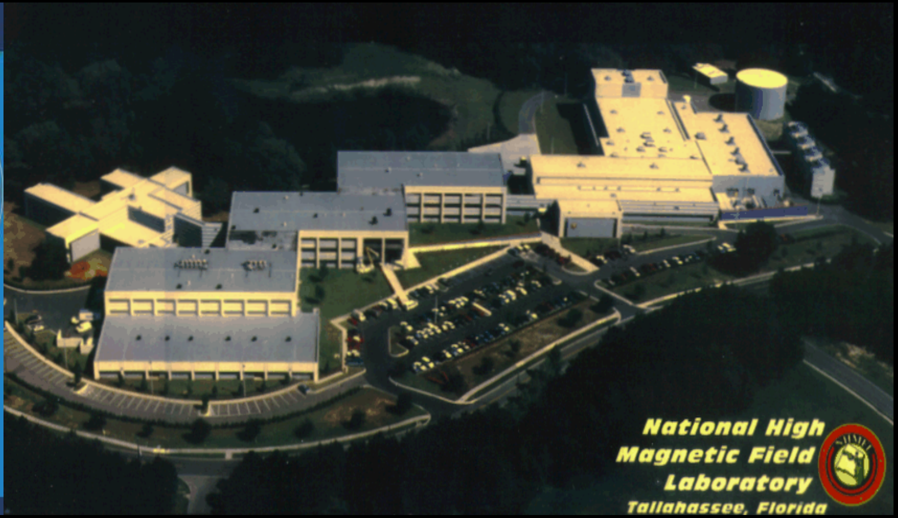


This graphic represents preliminary 2011 user data as of 11/2011



Outline

1. Motivation of studying the flows in helium-4
    - High Re number flows - model testing
    - Thermal counterflow – helium based cooling systems

2. Flow visualization in helium-4
    - Existing visualization techniques: progresses and issues
    - New visualization method using He_2^* molecules

3. Application of neutrons
    - Neutron-He3 absorption
    - Producing He_2^* clusters for velocity field measurement in helium

1. Motivation

- Why are we interested in the hydrodynamics of helium-4?

1. He4 is a very useful fluid material in high Re number turbulence research and model testing

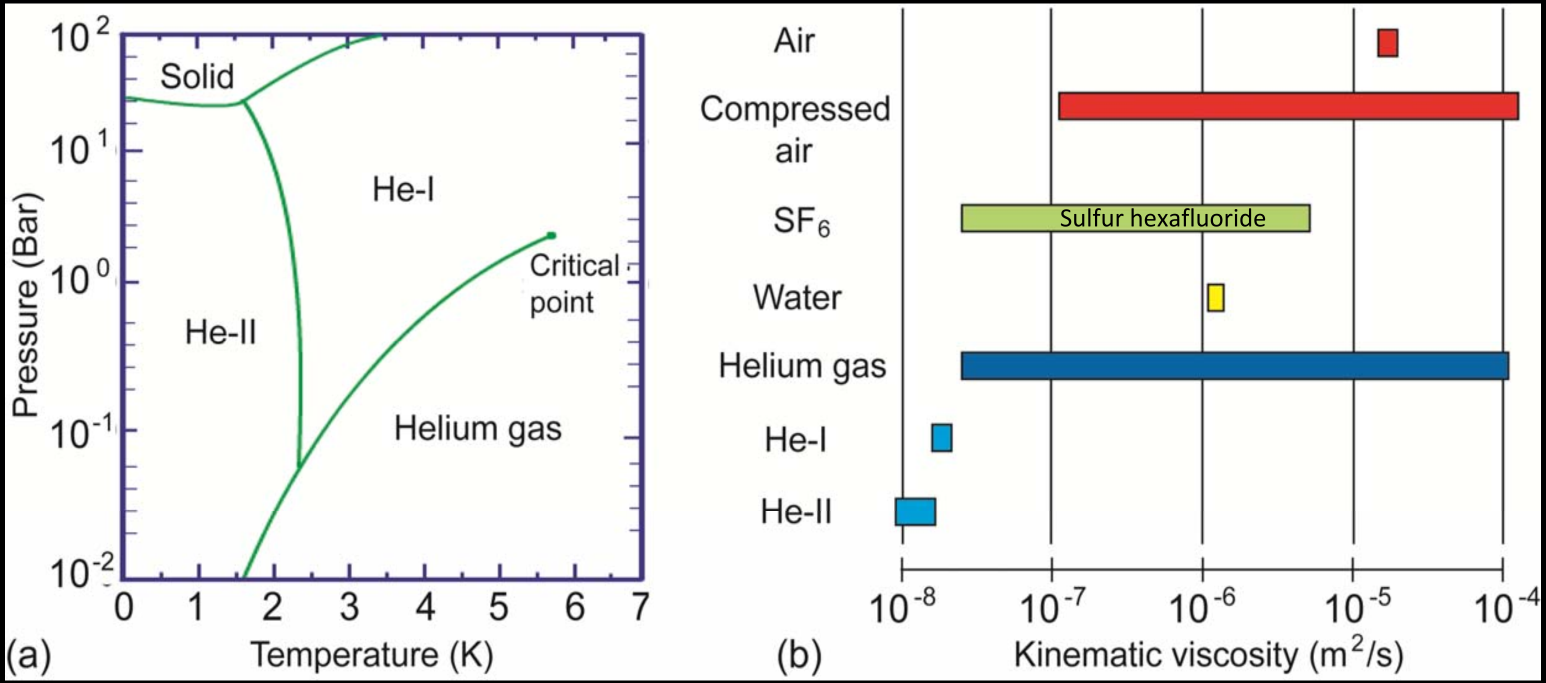
$$\mathrm{Re} \sim 10^{8} - 10^{9}$$

Many turbulent flows in nature has extremely high Reynolds numbers (Re). Studying these flows in laboratory requires either larger scale flow facilities or a fluid material with very small viscosity.

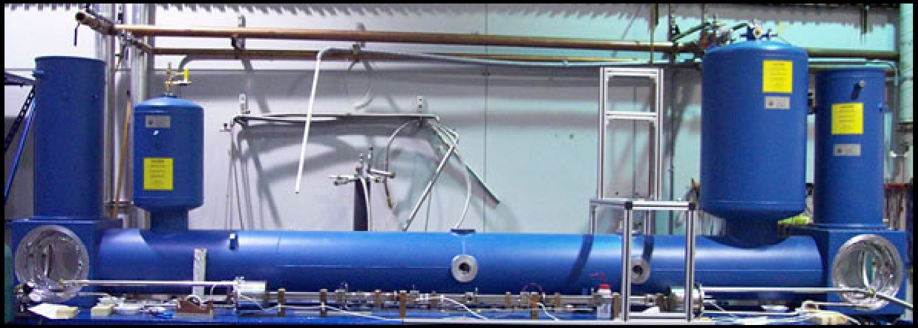
$$\mathrm{Re} = \frac{U \cdot L}{\nu}$$

Typical wind tunnel experiment with water or air can hardly achieve Re~10^6.

Liquid helium-4 has extremely small kinematic viscosity:



He-I denote the normal liquid phase, and He-II denote the superfluid phase. These two liquid phases all have small kinematic viscosity.



Channel flows with Re~10^7 has already been achieved in our cryogenics lab in He-I and He-II.

- Why are we interested in the hydrodynamics of helium-4?

2. Superfluid He4 is a superior coolant due to its counterflow hydrodynamics

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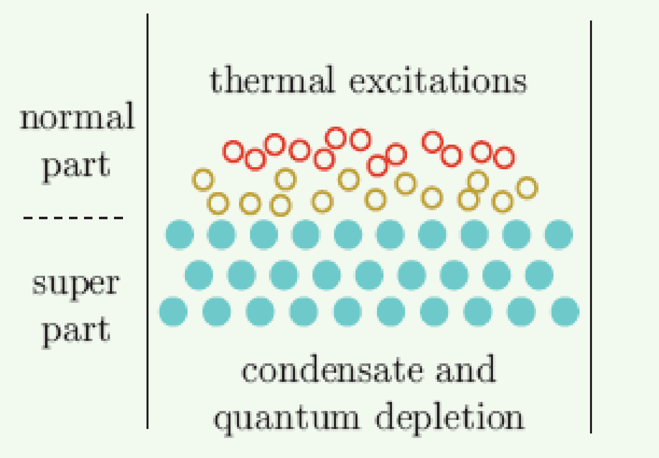
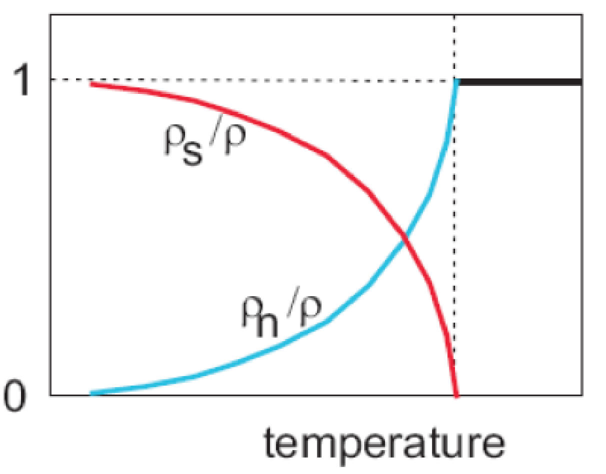
- He4 becomes superfluid below ~2.2 K
- There exist two components:
  - → Superfluid component (condensate)
  - → Normal-fluid component (excitations)



$$\rho = \rho_s + \rho_n$$



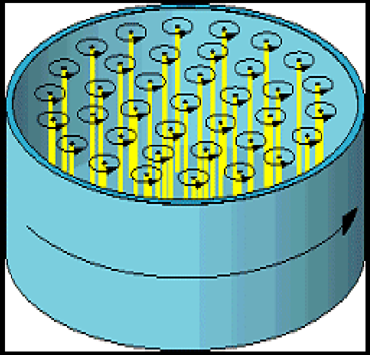
	Density	Velocity	Viscosity	Entropy
Superfluid	$\rho_s(T)$	$\mathbf{v}_s(\mathbf{r})$	0	0
Normal fluid	$\rho_n(T)$	$\mathbf{v}_n(\mathbf{r})$	$\eta_n(T)$	$s_n(T)$

Circulation in superfluid helium-4 is quantized:

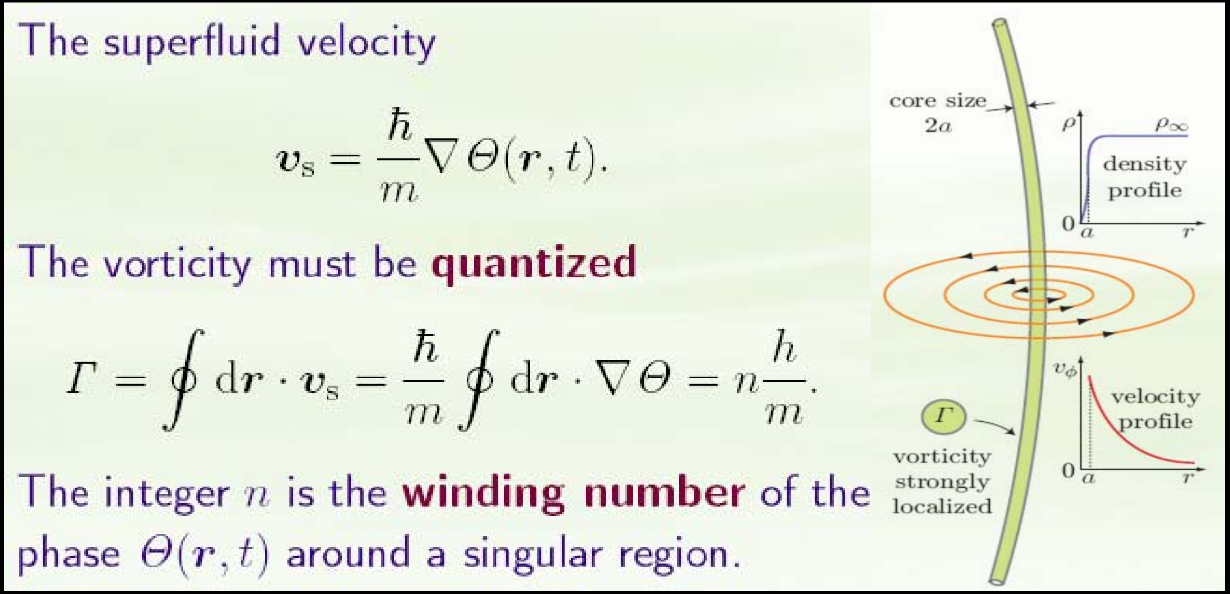
Superfluid can be described by a macroscopic wave function:

$$\psi(\vec{r},t)=\sqrt{n_0(\vec{r},t)}\,\exp\left[i\phi(\vec{r},t)\right]$$

Rotational flow of the superfluid component is subject to severe quantum restrictions: the quantization of circulation (Bose condensation)



$$\boxed{v=\frac{h}{2\pi m}\cdot\frac{1}{r}}$$



The superfluid velocity

$$\boldsymbol{v}_{\mathrm{s}}=\frac{\hbar}{m}\nabla\Theta(\boldsymbol{r},t).$$

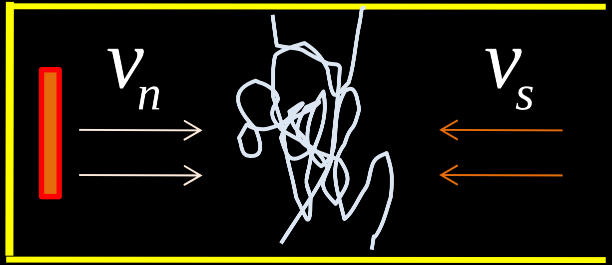
The vorticity must be **quantized**

$$\Gamma=\oint \mathrm{d}\boldsymbol{r}\cdot\boldsymbol{v}_{\mathrm{s}}=\frac{\hbar}{m}\oint \mathrm{d}\boldsymbol{r}\cdot\nabla\Theta=n\frac{h}{m}.$$

The integer n is the **winding number** of the phase $\Theta(\boldsymbol{r},t)$ around a singular region.

- Thermal counterflow:

Heat transfer in He-II is by counterflow : the superfluid moves towards the source of heat, where it is converted to normal fluid, which then flows in the opposite direction, carrying thermal energy.

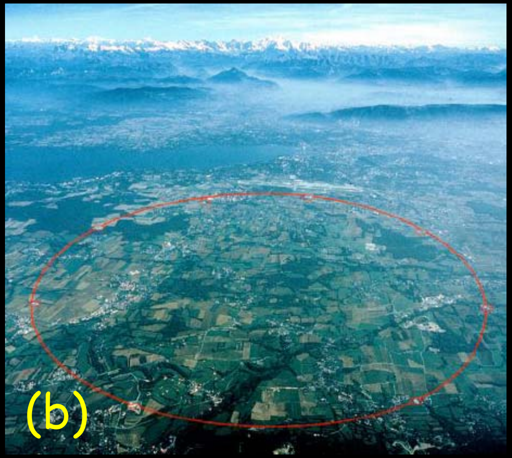


$$v_n = \frac{w/A}{\rho S T} \qquad v_s = \frac{\rho_n}{\rho_s} v_n$$

Turbulence in both fluids can affect the heat transfer !

- He-II has been used to cool a wide variety of devices:

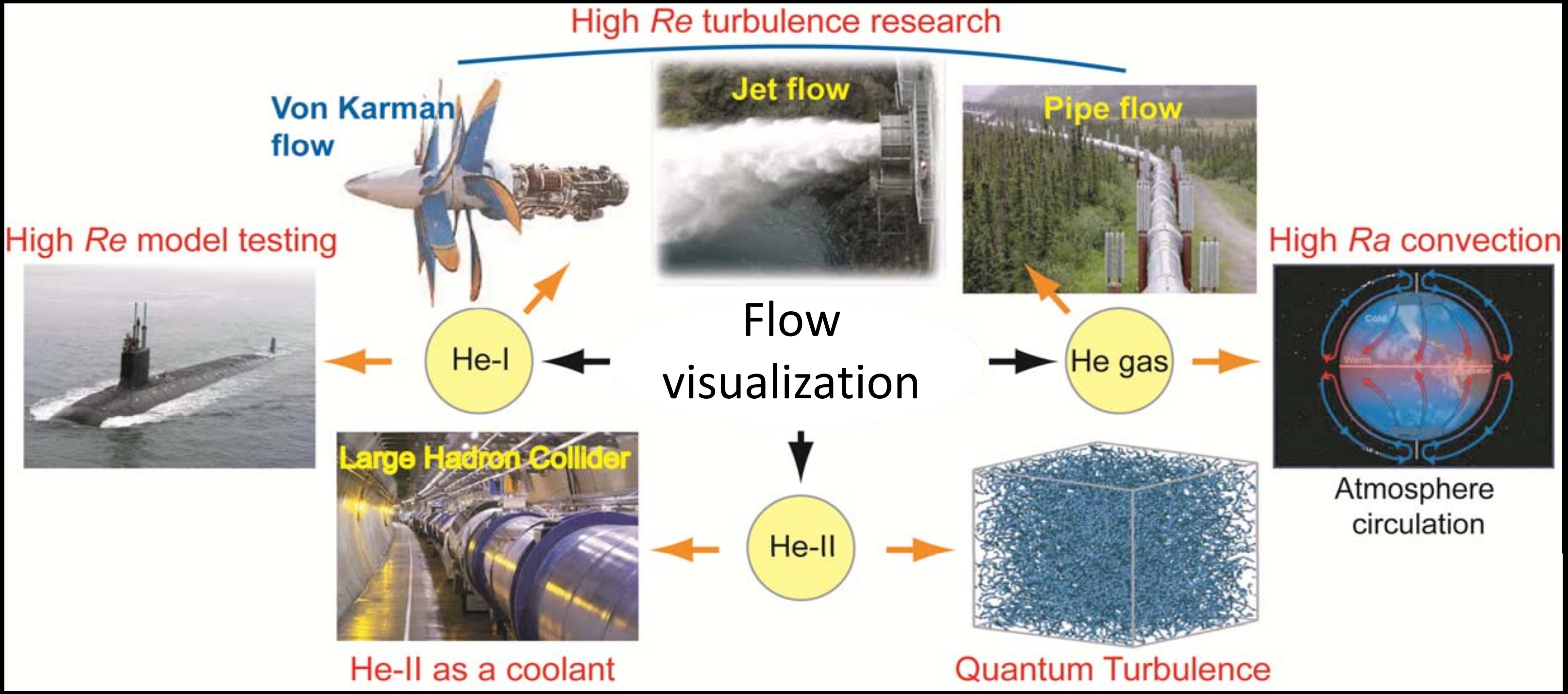
IRAS
LHe-4: 720 liters,
T=1.6 K



CERN: LHC
(27 Km ring)

LHe-4:
700,000 liters
T=1.8 K

- Studying the hydrodynamics of helium-4 can benefit various science and engineering fields

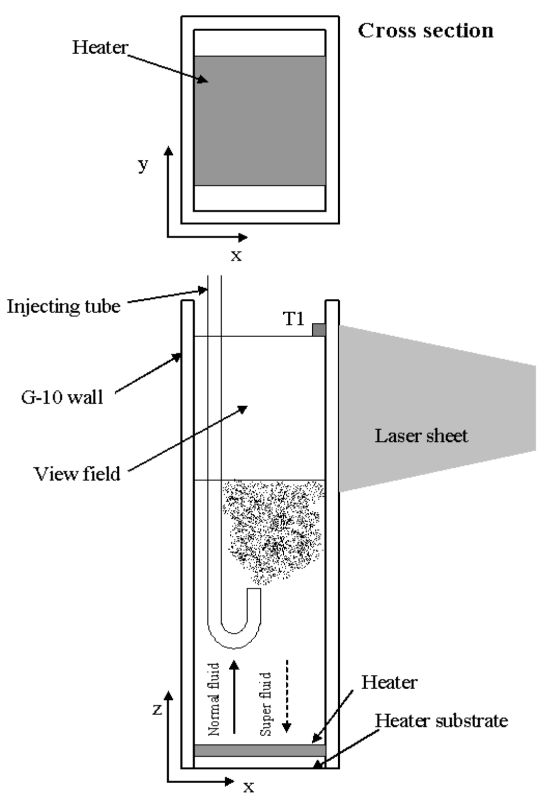


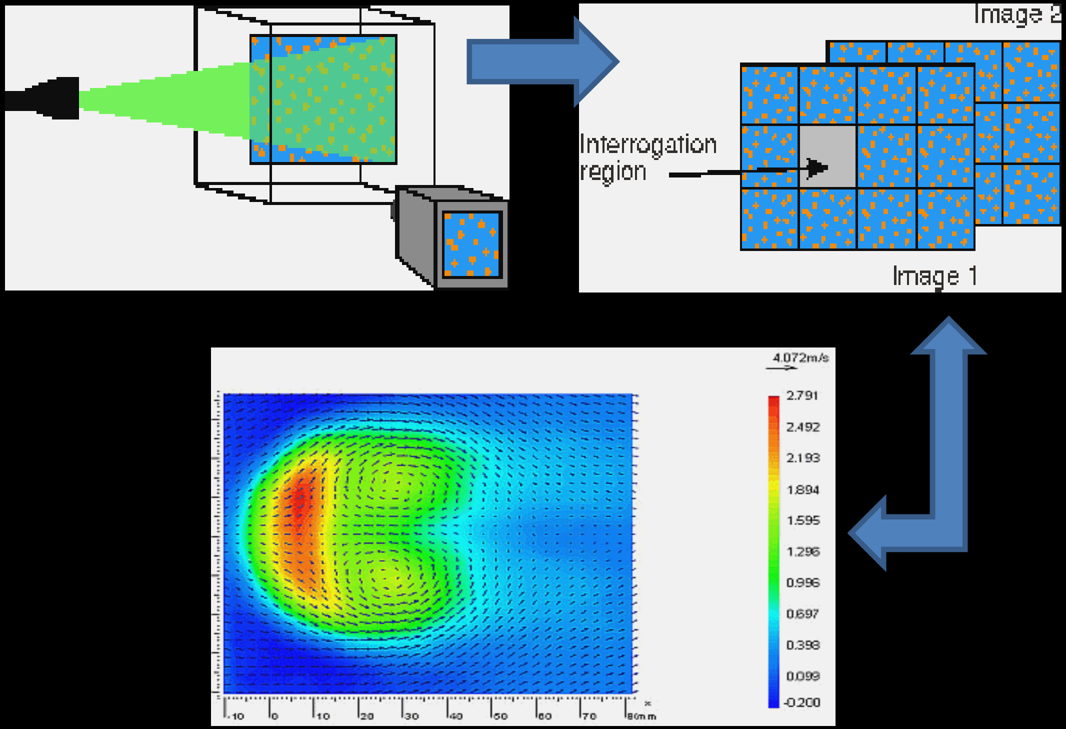
Need precision flow measuring tools in order to unlock the full potential of helium-4 !

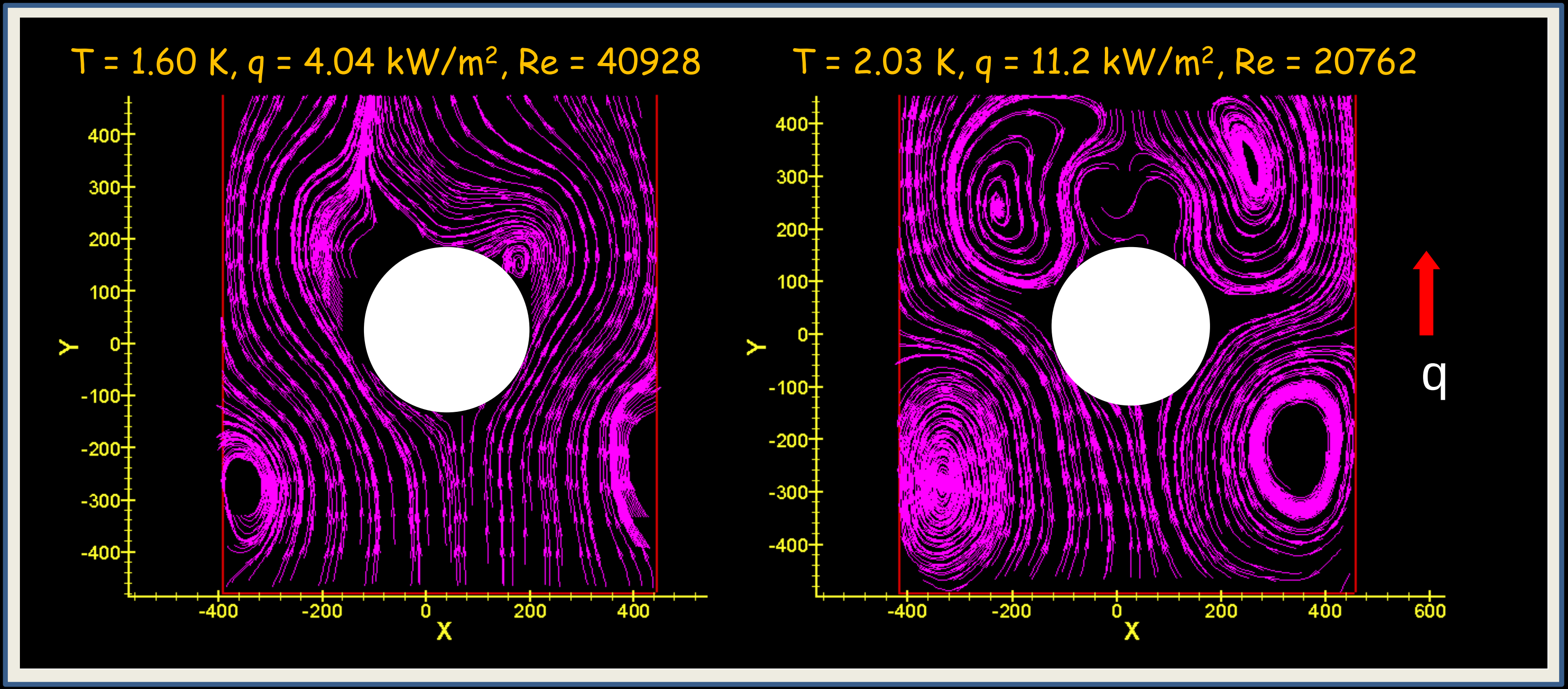
2. Flow visualization in helium-4

- Existing visualization techniques using micron-sized tracers

(1) Particle imaging velocimetry (with polymer microspheres, solidified hydrogen ice particles)







T = 1.60 K, q = 4.04 kW/m^2, Re = 40928

T = 2.03 K, q = 11.2 kW/m^2, Re = 20762

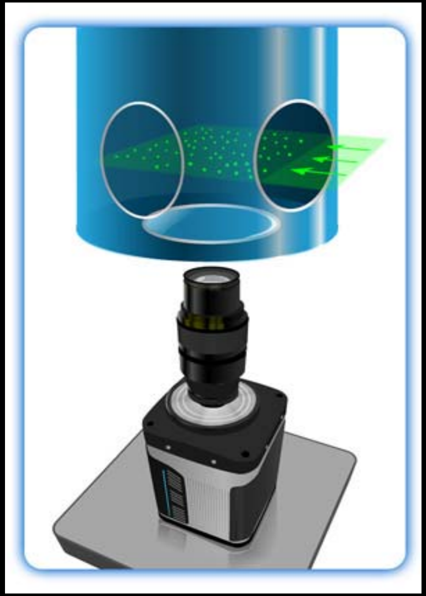
Zhang and Van Sciver, *Nature Physics* ***1*****,** ***36 (2005).***

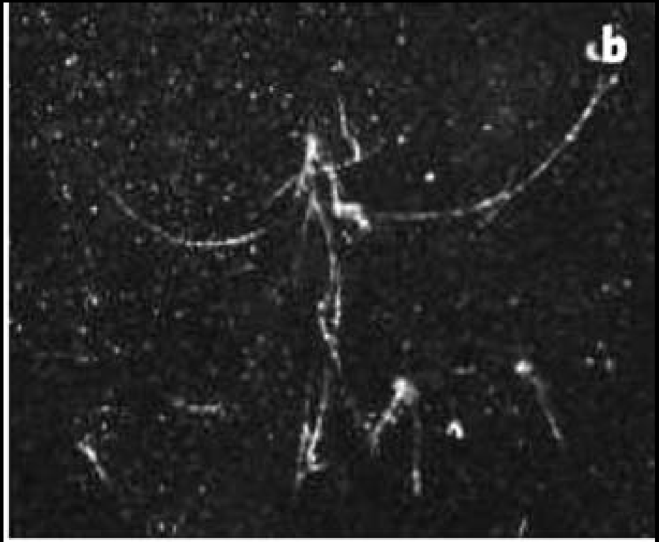
The velocity field of the normal fluid can be determined for the first time.

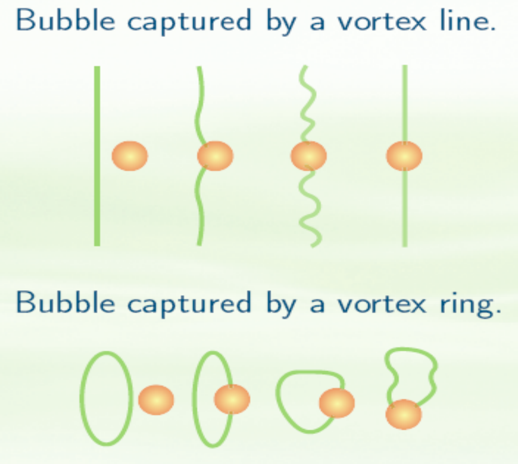
* In thermal counterflow, measured tracer velocity is slower than the expected normal-fluid velocity.

* Flow across cylinder revealed eddies that appeared upstream in front of the cylinder.

(2) Particle tracking (with hydrogen isotopes ice particles)







Bewley, Lathrop, and Sreenivasan *Nature* ***441*, *588 (2006)***

PTV was first applied to helium by Lanthrop's group at Maryland Univ.

* Experiment was conducted at smaller heat current (less vortices).

* Particles are observed to bind to vortex lines due to Bernoulli's effect ➔ direct visualization of quantized vortices.

* Quantized vortex lines were imaged.

i) Thermal counterflow.
Ramping up the heat.

ii) Visualization of quantized vortex lines.
Studying vortex line connection.

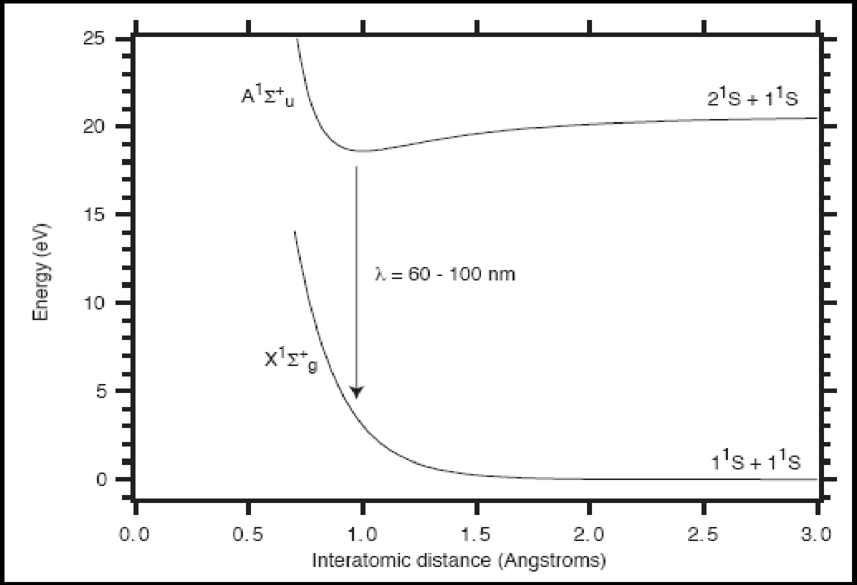
Challenges:

* Heat load accompanying particle injection → inapplicable at low T.

* Particles can aggregate.

* Particles interact with both the normal fluid and the vortices → For flows in which the normal fluid, the superfluid, and the vortices all have different velocity fields, tracer behavior becomes hard to interpret.

• Flow visualization using He2 molecules



- Metastable He_2^* molecules can be easily produced as a result of ionization or excitation in LHe4:

$e^- + He^+ + He \rightarrow He^* + He \rightarrow He^*_2$

singlet state $A^1\Sigma_u^+$ lifetime: ~10 ns

triplet state $a^3\Sigma_u^+$ lifetime: **~13s**

Methods for tracer injection:

- Radioactive sources: α particles, β particles, gamma rays, neutrons…
- Electrical discharge from a sharp needle in LHe4.
- Laser field-ionization using a femtosecond laser pulse.

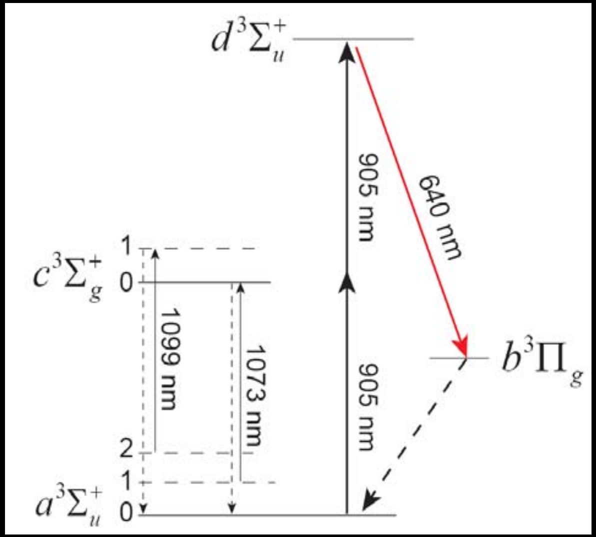
(low heat load and applicable at low T)

He_2^* molecules as tracers

- He_2^* molecules form little bubbles in LHe. (R~6Å)
  small effective mass and size in LHe4 => $a^3\Sigma_u^+$ does not disturb fluid !
- Molecules are neutral particles.
  no forces other than the interaction with fluid, no space charge effect.
- Helium molecules do not aggregate.
  Two helium molecules decay (Penning ionization) when they meet together.
- Above 1K, He_2^* molecules trace the normal-fluid component only
  Viscous relaxation time (roughly): $\tau = \dfrac{R^2 \rho_{\mathrm{He}}}{9\mu_{\mathrm{n}}}$ ~ 5ps @ 1.5K ➔ Vortex interaction is negligible !
- Molecule bubbles can be trapped on vortex lines below 0.6 K.
  Molecules are similar in size to He^+, trapping energy on vortices (~20K).
  (D. Zmeev, et al, Phys. Rev. Lett., 110, 175303 (2013))

➔ imaging vortices at low T !

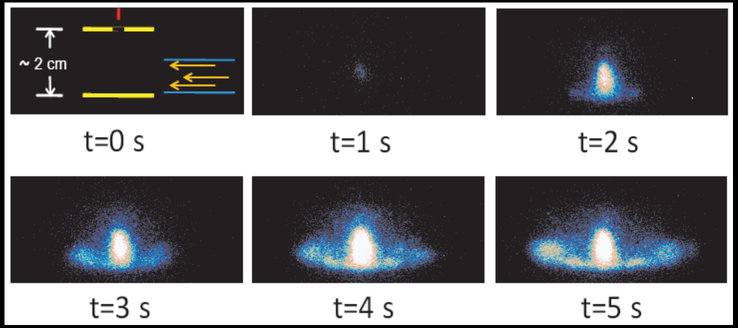
Imaging He_2^* molecules: Laser-induced fluorescence



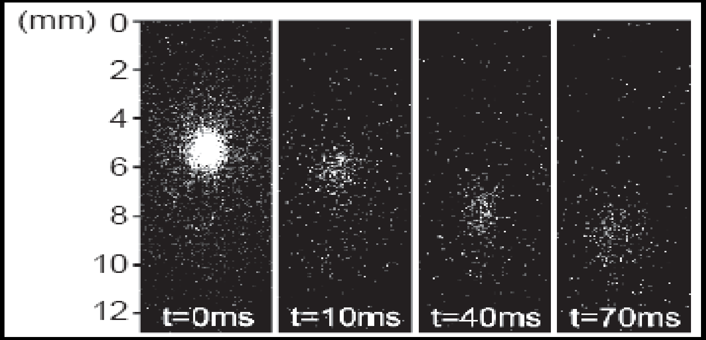
W.G. Rellergert *et al.*, Phys. Rev. Lett, 100 (2008).

For molecules in the triplet ground state a(0):

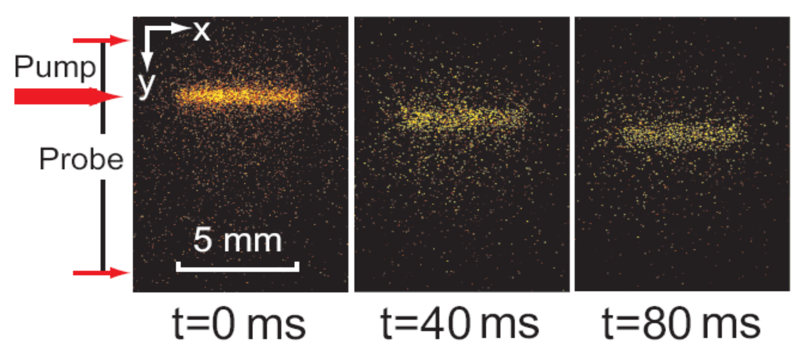
- A 905 nm pulsed laser is used to drive a cycling transition.
- Fluorescent light emitted at 640 nm.



Guo, et al., J. Low Temp. Phys., 158, 346 (2009)



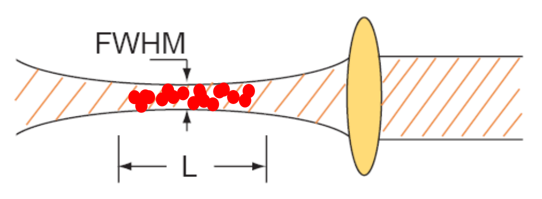
Guo, *et al.*, Phys. Rev. Lett., 102, 235301 (2009)



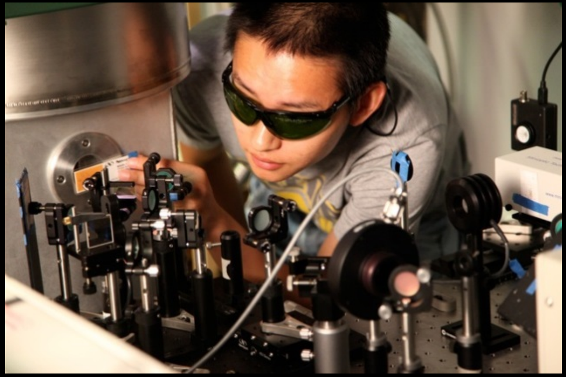
Guo, et al., Phys. Rev. Lett. 105, 045301 (2010).

• Recent development: He2 tracer-line tracking technique

Femtosecond laser field ionization in helium:



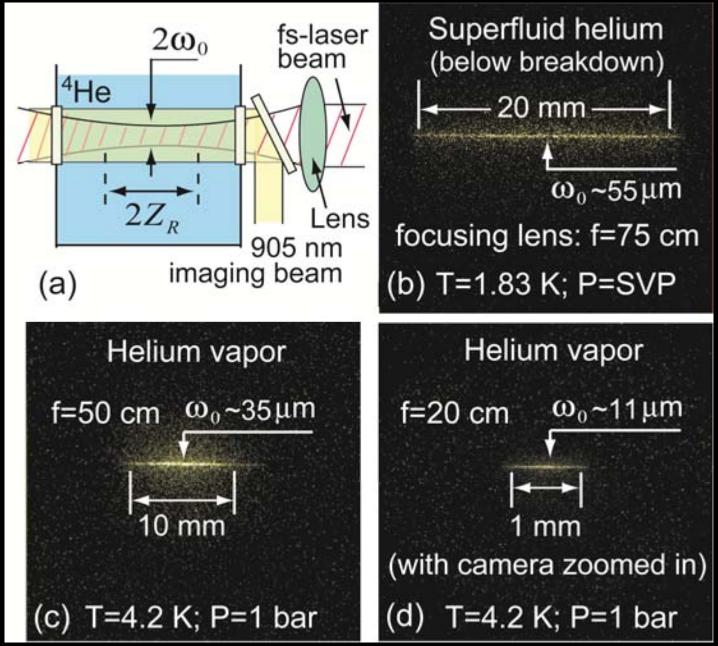
$$I \geq 10^{13}\ \mathrm{W/cm^2}$$



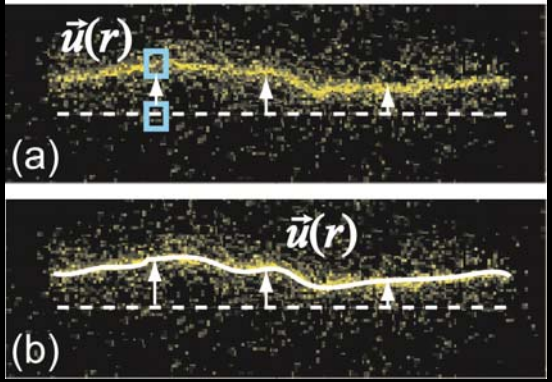
Pulse length: 35 fs

Pulse energy: up to 4 mJ

Rep rate: up to 5 kHz



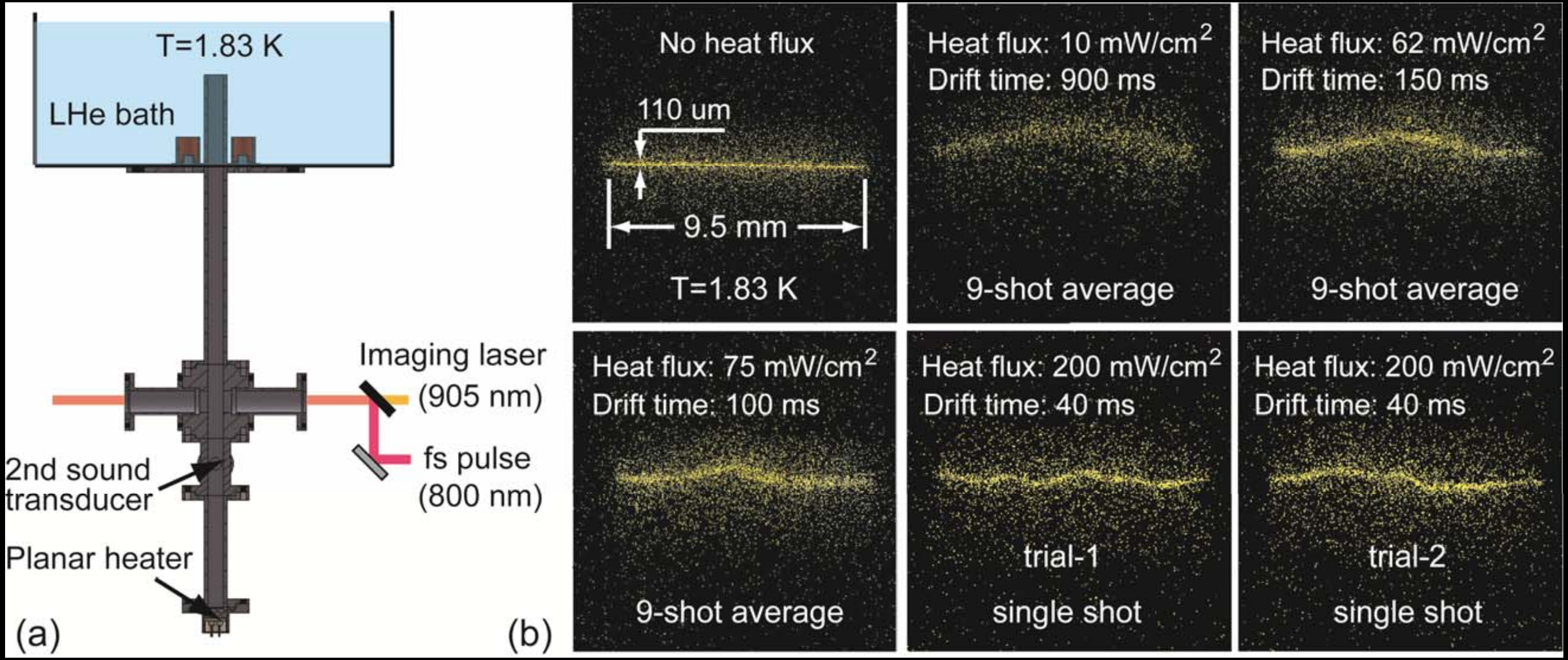
J. Gao, et al., Rev. Sci. Instrum. 86, 093904 (2015)



W. Guo, *et al.*, PNAS, 111, 4653 (2014)

- Thin tracer lines can be produced and tracked, allowing high precision flow field measurement.
- This technique is applicable to He-I and gaseous helium.

- Application to the study of thermal counterflow



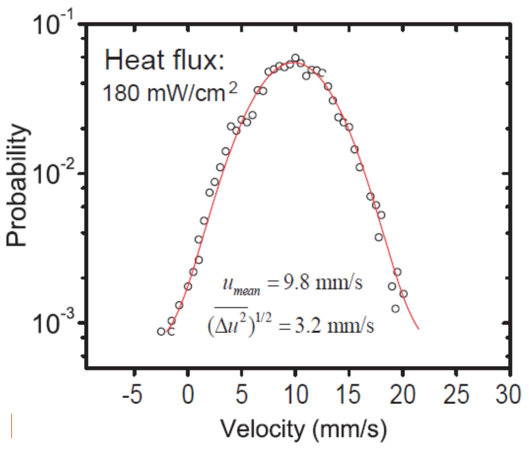
A. Marakov, G. Jian, et al., Phys. Rev. B 91, 094503 (2015).

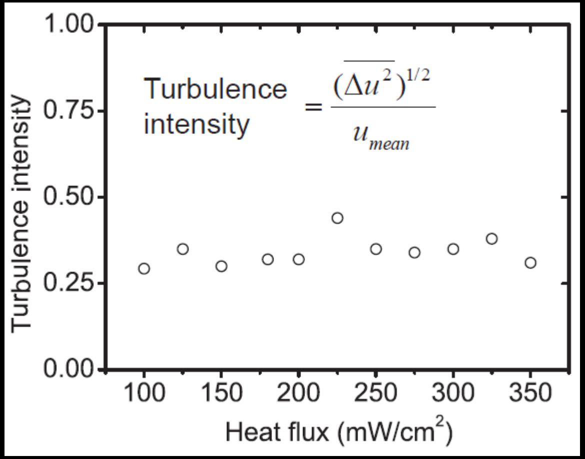
Major observations:

1) Three distinct velocity profiles of the normal fluid were observed:

Parabolic laminar profile → Tail-flatten laminar profile → Distorted turbulent profile

2) The velocity PDF in turbulent normal fluid is found to be a Gaussian. The turbulence intensity is measured to be about 35%.



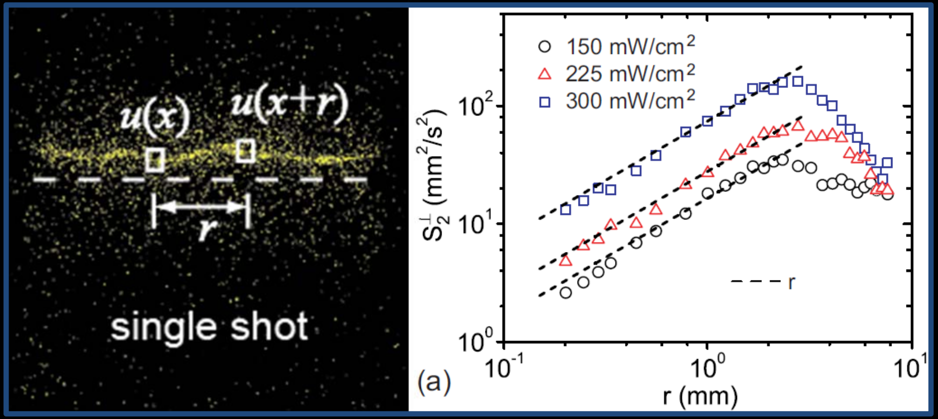


3) The 2nd order transverse structure function is calculated

$$S_2^{\perp}(R,r)=\overline{\left\langle \left(u(R+r)-u(R)\right)^2 \right\rangle}$$

$$\boxed{S_2(r)\propto r^n \Longleftrightarrow E(k)\propto k^{-(n+1)}}$$

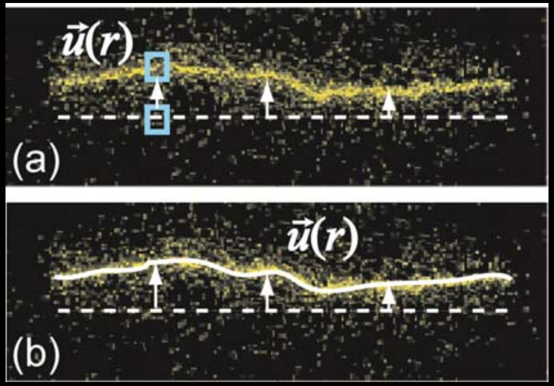
$$\Rightarrow \quad \tilde{E}(k)\propto k^{-2}$$



A. Marakov, G. Jian, et al., Phys. Rev. B 91, 094503 (2015).

3. Application of neutrons

Issues with the He2 tracer line imaging method:



i) Only the velocity component perpendicular to the tracer line can be measured.

ii) It cannot produce full velocity field information; it is hard to map the shape of turbulent eddy structures.

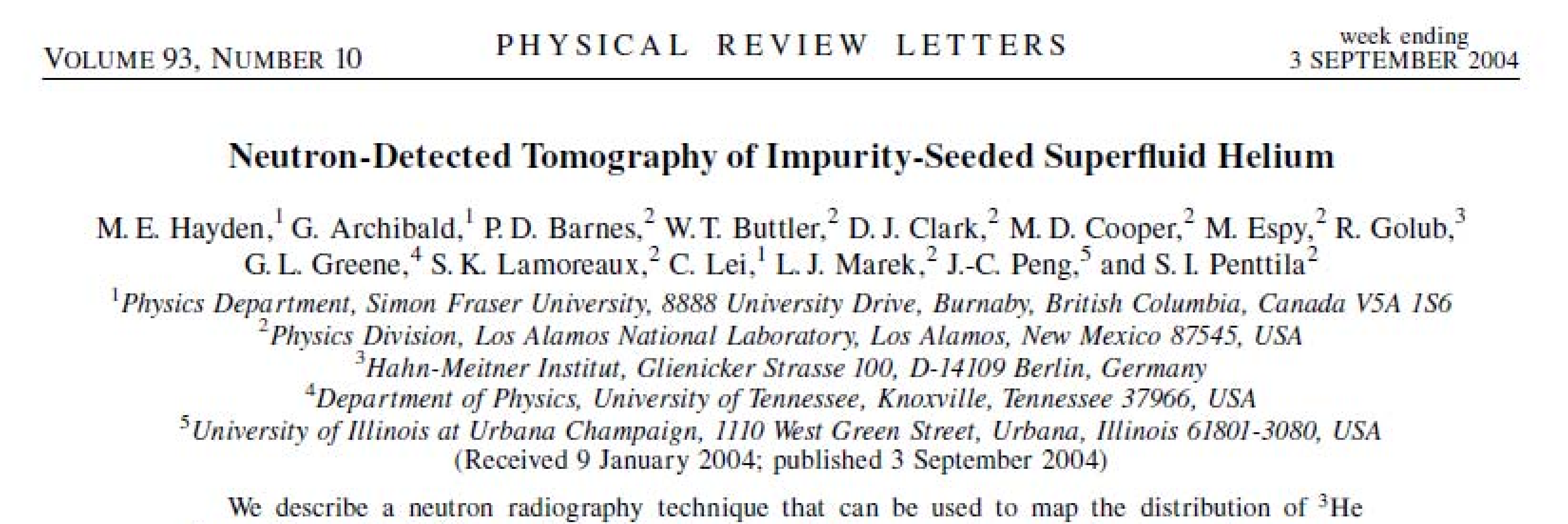
It is strongly desired to develop a method for making PIV measurement of the normal fluid. This measurement should not be affected by the presence of vortices.

Idea-1: using He2 molecules for PIV measurement?

No, so far fluorescence imaging is not sensitive enough for tracking individual He2 molecules.

Idea-2: using small clusters of He2 molecules for PIV !

Yes, small clusters of He2 molecules can be produced in helium via neutron-He3 absorption.



VOLUME 93, NUMBER 10 PHYSICAL REVIEW LETTERS week ending 3 SEPTEMBER 2004

Neutron-Detected Tomography of Impurity-Seeded Superfluid Helium

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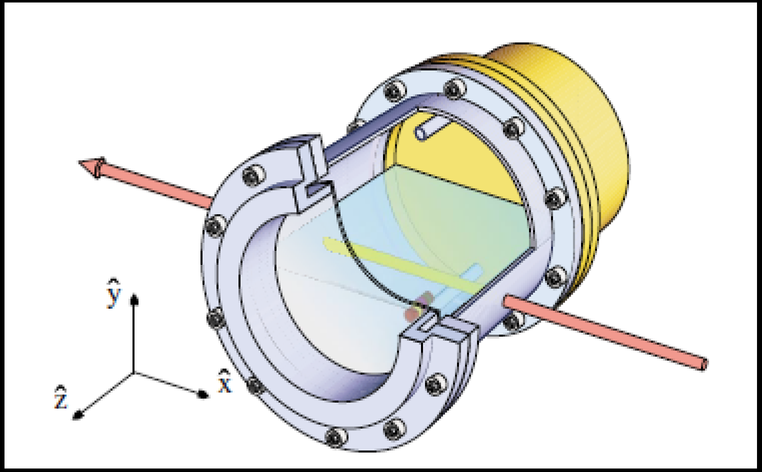
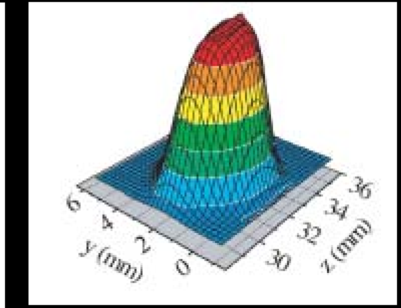
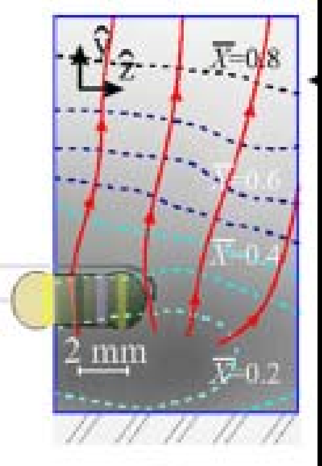
(Received 9 January 2004; published 3 September 2004)

We describe a neutron radiography technique that can be used to map the distribution of ^{3}He impurities in liquid ^{4}He, providing direct and quantitative access to underlying transport processes. Images reflecting finite normal- and superfluid-component ^{4}He velocity fields are presented.



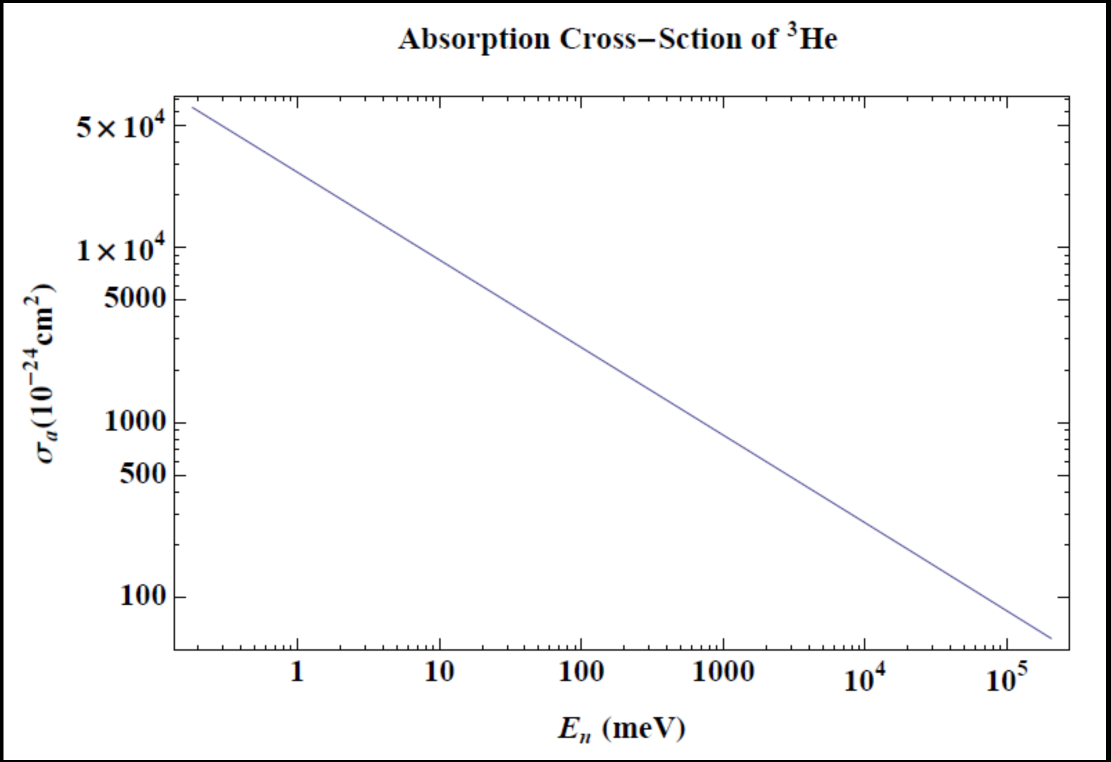


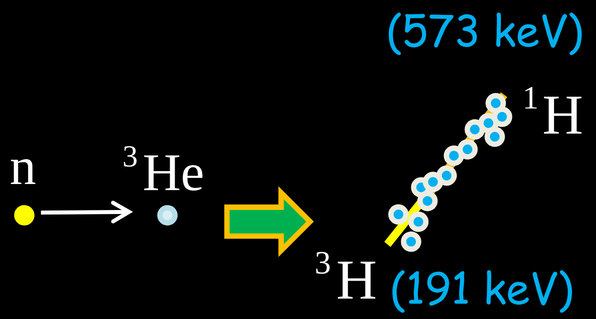


* Neutron absorption on He3 atoms:

leads to the production of two energetic particles: ${}^{1}\mathrm{H}$ and ${}^{3}\mathrm{H}$. These two particles excite and ionize He atoms along their tracks, leading to the creation of He2 molecules:

$$\mathrm{n}+{}^{3}\mathrm{He}\rightarrow{}^{3}\mathrm{H}+{}^{1}\mathrm{H}+764\ \mathrm{keV}$$





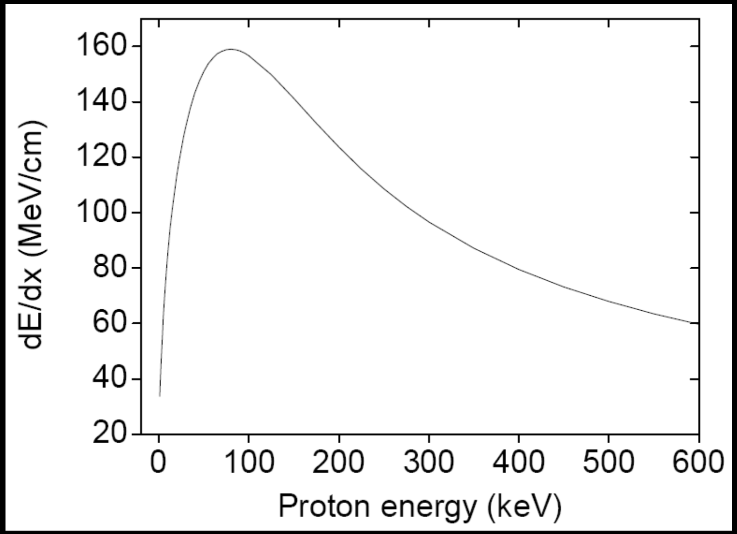
The absorption cross-section drops with increasing neutron energy. For cold neutrons ~ 0.3 meV

$$\sigma_{\mathrm{He}^3-\mathrm{n}}\sim5\times10^{-20}\mathrm{cm}^2$$

- Estimation of the Size of the resulted He2 molecular clusters:

i) The range of a 573 keV proton in liquid helium-4

$$x=\int_0^{E_0}\left(\frac{dE}{dx}\right)dx \simeq 57\,\mu\text{m}$$

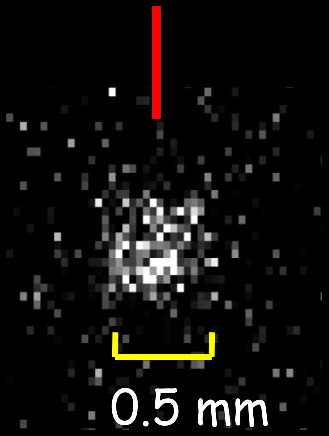


ii) The range of a 191 keV tritium is estimated to be $\leq 20\,\mu\text{m}$

He2 Cluster size ~ 100 um

- Brightness of the clusters:

Note that about 10^4 triplet molecules are produced along the tracks of H and H3.



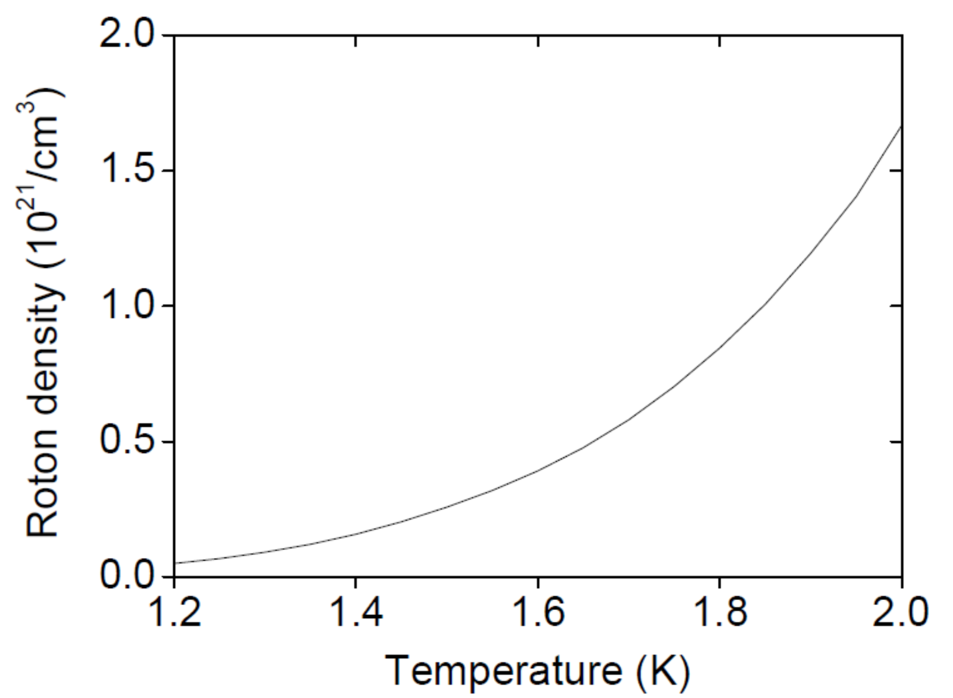
In the past, we created a small cloud of He2 tracers by pulse a sharp metal needle in He-II.

Molecule density is ~ 10^7/cm^3. The number of molecules is about 1.2×10^3

A He2 cluster size ~ 100 um and with 10^4 molecules should yield brighter images !

- Number density of the He2 molecular clusters:

Cluster density can be varies by changing He3 concentration. Note: He3 density should be far smaller than roton density in order not to alter the fluid property!



(note: number density of He-II is $\sim 2.2\times10^{22}\mathrm{cm}^{-3}$)

- Cold neutron source:

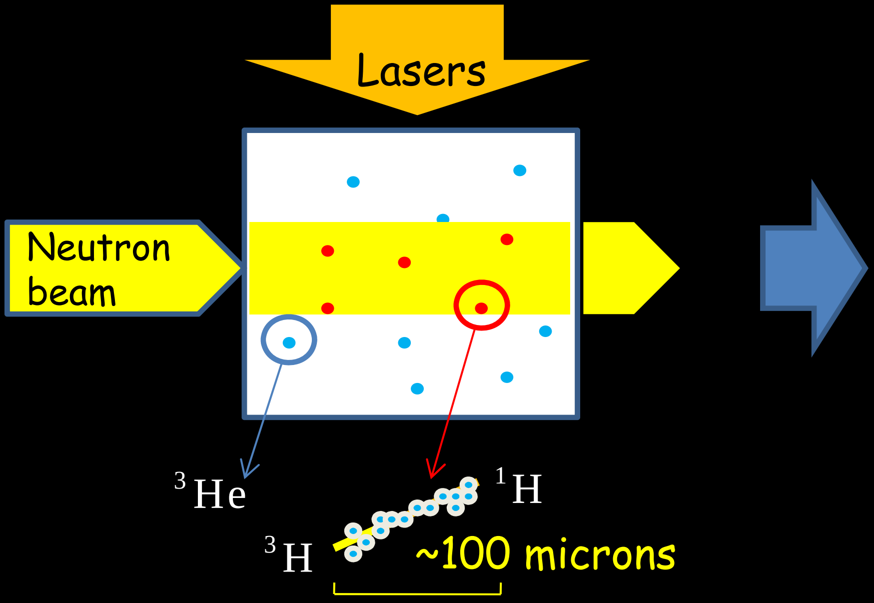
$\sigma_{\mathrm{He}^3-\mathrm{n}} \sim 5\times10^{-20}\mathrm{cm}^2$

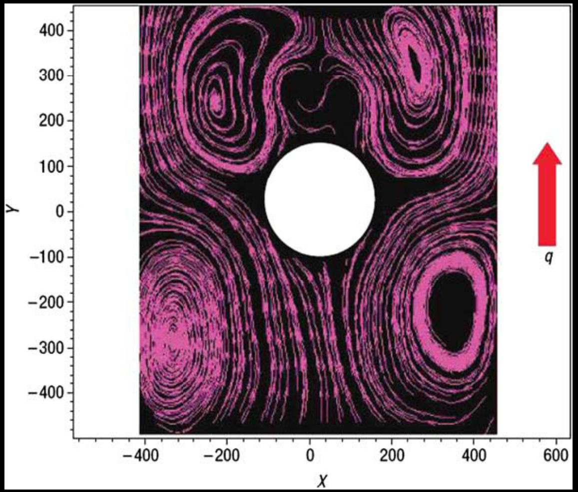
Flux ~ 10^4/cm^2
(per pulse, or per illumination)

- He3 density ~50 ppm
(< 1% of roton)

⇒ 500 clusters/cm^3 !

- A new way to do PIV/PTV in superfluid helium-4:





Zhang and Van Sciver, *Nature Physics* ***1*****,** ***36 (2005).***

Procedures:

i) Dope the He-II with suitable concentration of He3 atoms.

ii) Pass the neutron beam to create small clusters of He2 molecular tracers.

ii) Image the He2 tracer clusters with laser-induced fluorescence.

iv) Map the normal-fluid velocity field using PIV or PTV.

Summary

1) Studying the hydrodynamics of Lhe is of both scientific and practical significance.

2) Flow visualization technique has been developed based on the use of He2 molecular tracers.

3) By using neutron-He3 absorption, large amount of small clusters of He2 tracers can be produced, which allows for the determination of complete velocity field of the normal fluid.

END

Questions?