# NMR Measurement of Vortex Formation and Dynamics in Rotating Superfluid $^3$He-B as a function of Vortex Damping

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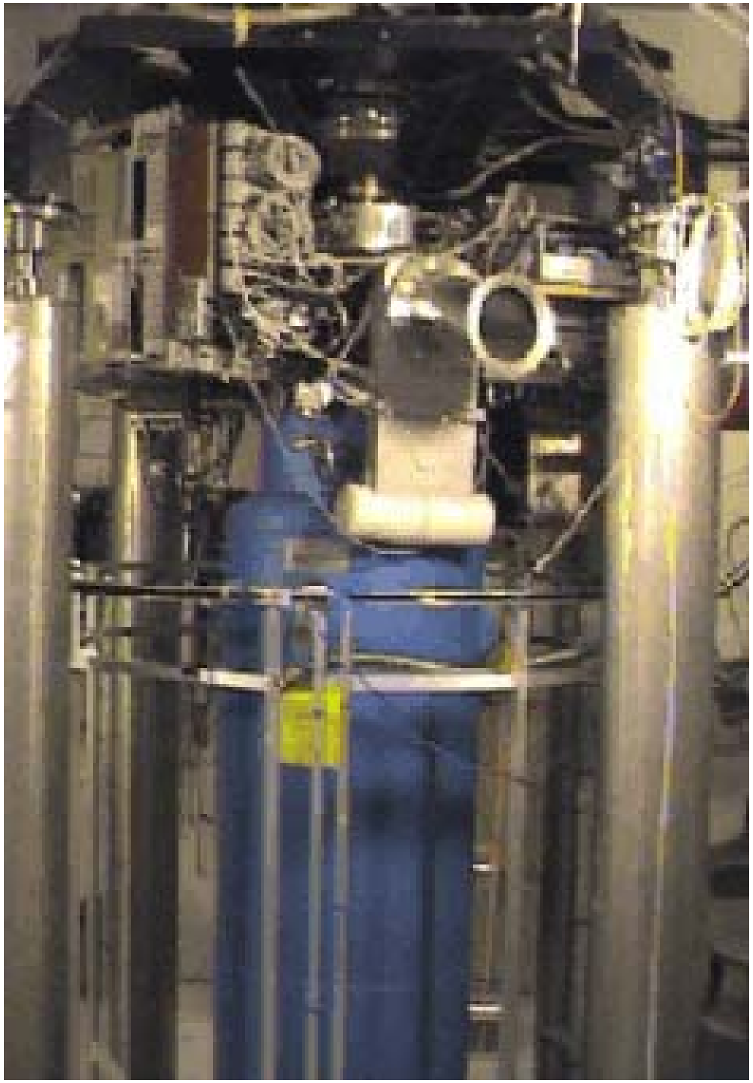
# Overview

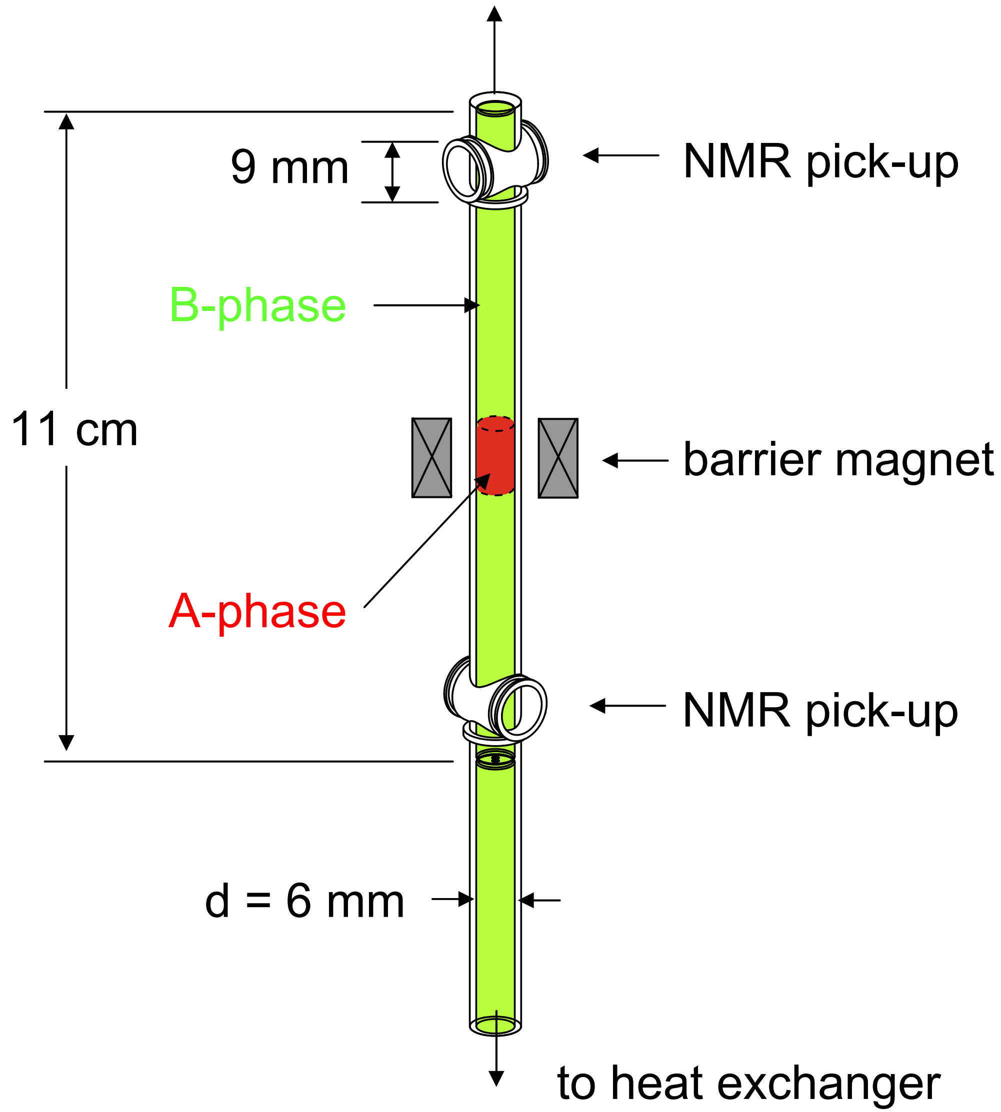
- The experiment
- NMR Measurement
- Vortex injection and evolution at high T
- Vortex injection and evolution at low T
  - Multiplication
  - propagation as a front
- Conclusions

# The Rota cryostat

- Superfluid below 2.5 mK:
  - Dilution refrigerator for precooling
  - Adiabatic nuclear demagnetization cooling for superfuid $^3$He
- Rotation up to 4 rad/s
- Creation of flow with rotation
  - normal component follows the container
  - superfluid at rest until vortices form



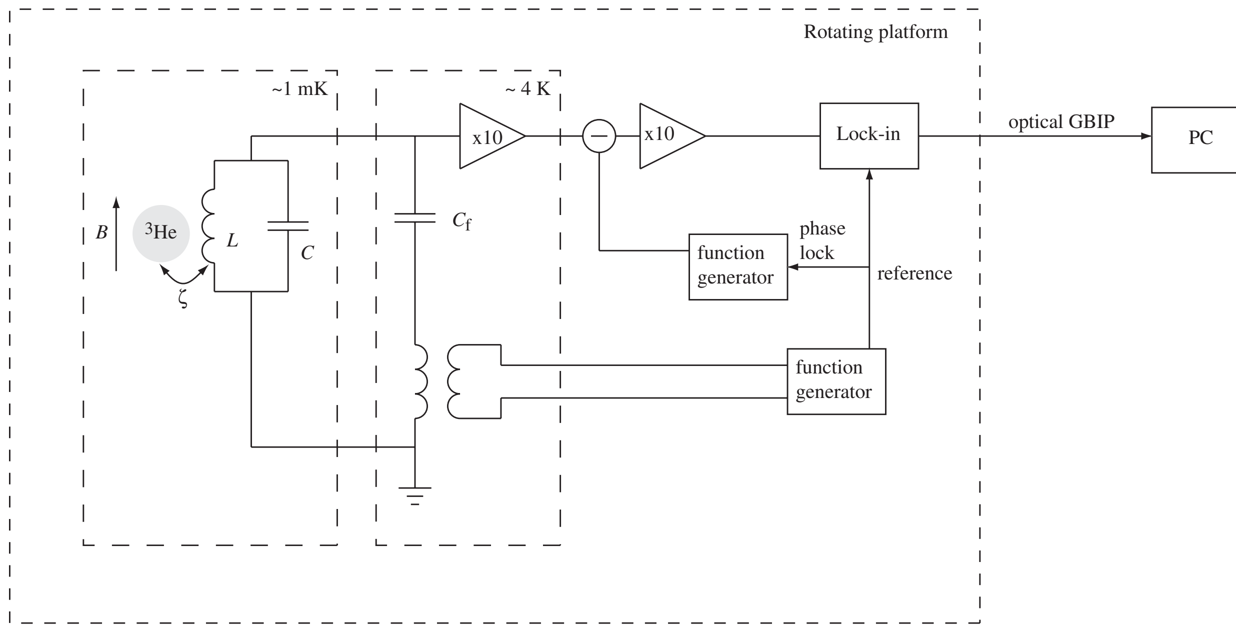
# Experimental setup




- Vortex injection through:
  1. Unstable phase boundary
  2. Neutron absorption
  3. Remnant vortices
  4. Instability at wall
- NMR detection:
  - Number of vortices
  - Configuration
- Two detectors: evolution of the vortex configuration in time and space

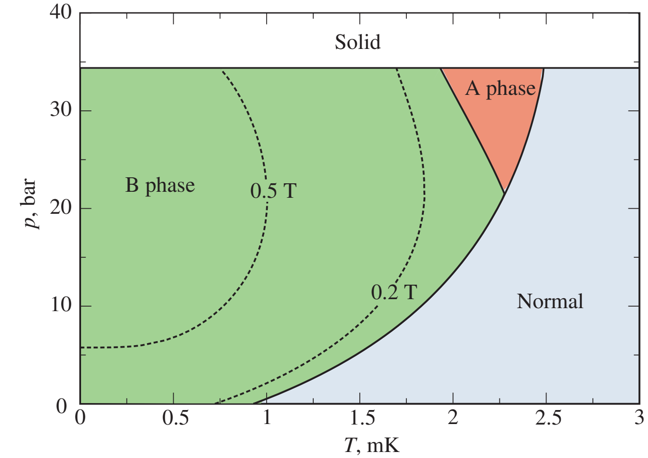
# CW-NMR

- High Q LC resonator for pick-up
- Sweep magnetic field
- Cold preamplifier (4K)



# NMR in $^3$He-B

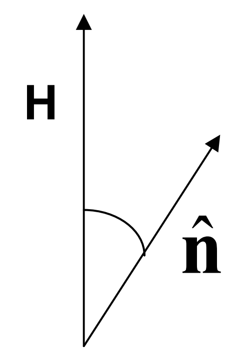
- Order parameter of the form $\overleftrightarrow{\mathrm{R}}(\hat{\mathbf{n}},\theta)$
  - The symmetry axis $\hat{\mathbf{n}}$ forms the texture
- Resonance frequency for NMR ( $H >> H_D \approx 3\,\mathrm{mT}$ ):




$$\omega \approx \omega_0 + \frac{\Omega_B^2}{2\omega_0}\sin^2\,\beta$$

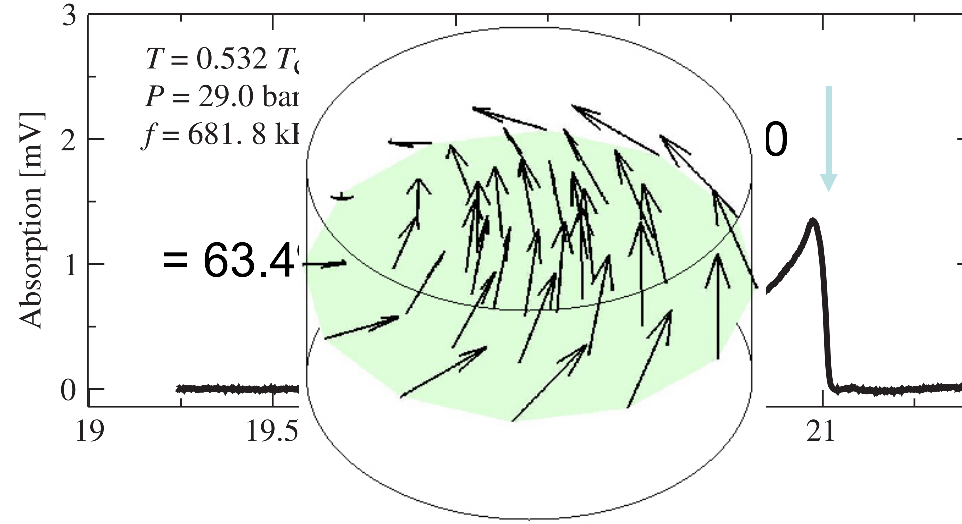
$_0$ Larmor frequency

$_B$(p,T) Leggett frequency




vortex lines → flow pattern → $\hat{\mathbf{n}}$ texture → NMR

# Flare out texture




**Magnetic field:**

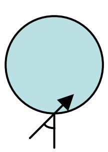
$$F_H = -a \int d^3\mathbf{r} (\hat{\mathbf{n}} \cdot \mathbf{H})^2$$

$\rightarrow \quad \hat{\mathbf{n}} \parallel \mathbf{H}$

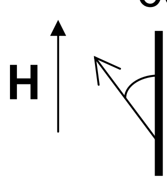
**Surfaces:**

$$F_s = -d \int d^2\mathbf{r} \left( \mathbf{H} \cdot \overleftrightarrow{R} \cdot \hat{\mathbf{s}} \right)^2$$

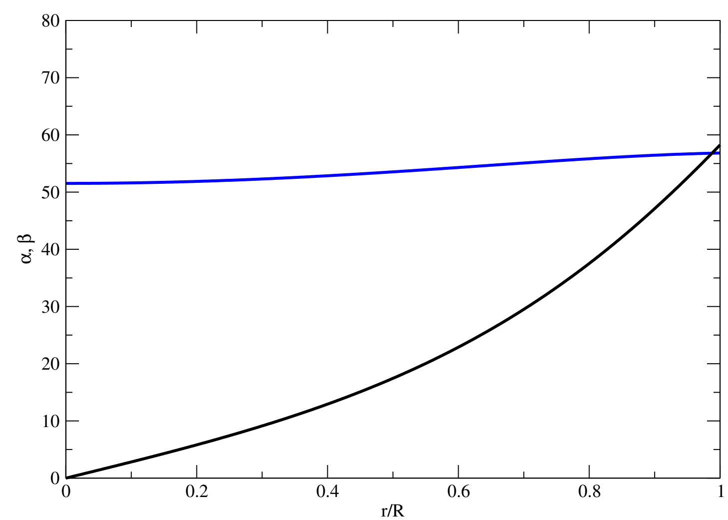
$\rightarrow$



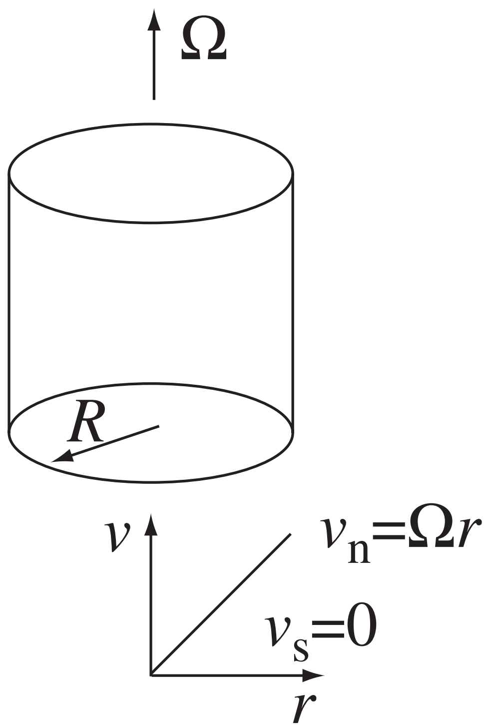
=60º

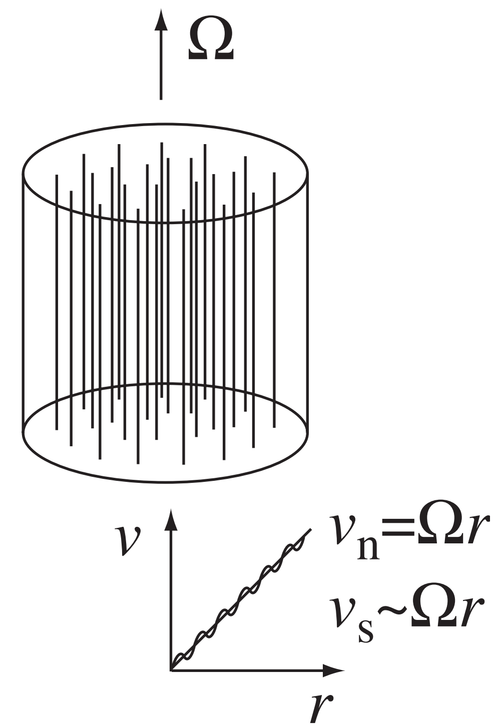



=63.4º



# Vortex lines in rotating flow



# Vortex lines and counterflow

**Flow:**

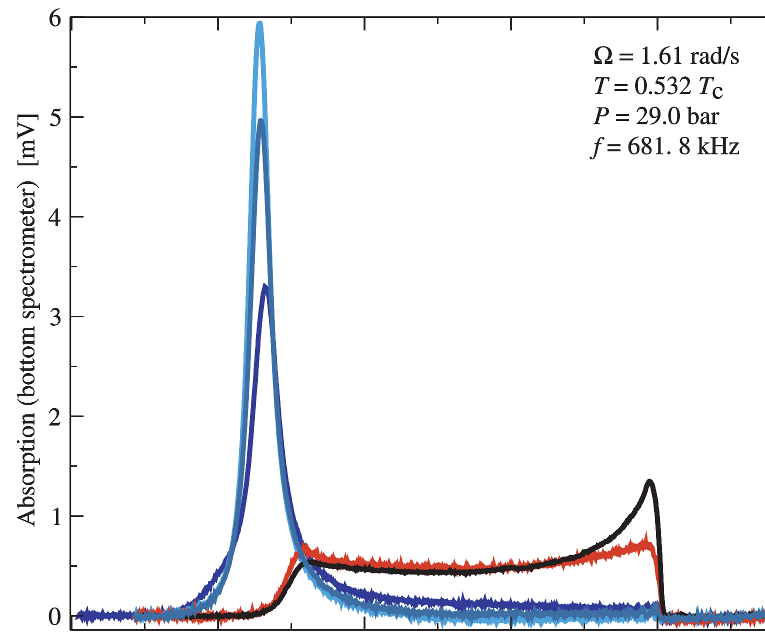
$$F_v = -\frac{2a}{5v_D^2}\int d^3\mathbf{r}\left(\mathbf{H}\cdot\overleftrightarrow{R}\cdot\mathbf{v}\right)^2$$

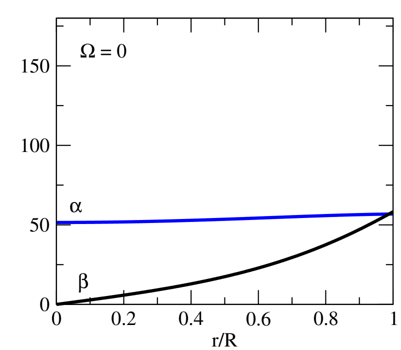
In rotating counterflow the preferred orientation = 63.4° (the same as for the wall but Differs by 90° → texture transitions)

**Vortex lines:**

$$F_v = \int_c d^3\mathbf{r}\,\lambda\left(\mathbf{H}\cdot\overleftrightarrow{R}\cdot\hat{\mathbf{l}}\right)^2$$

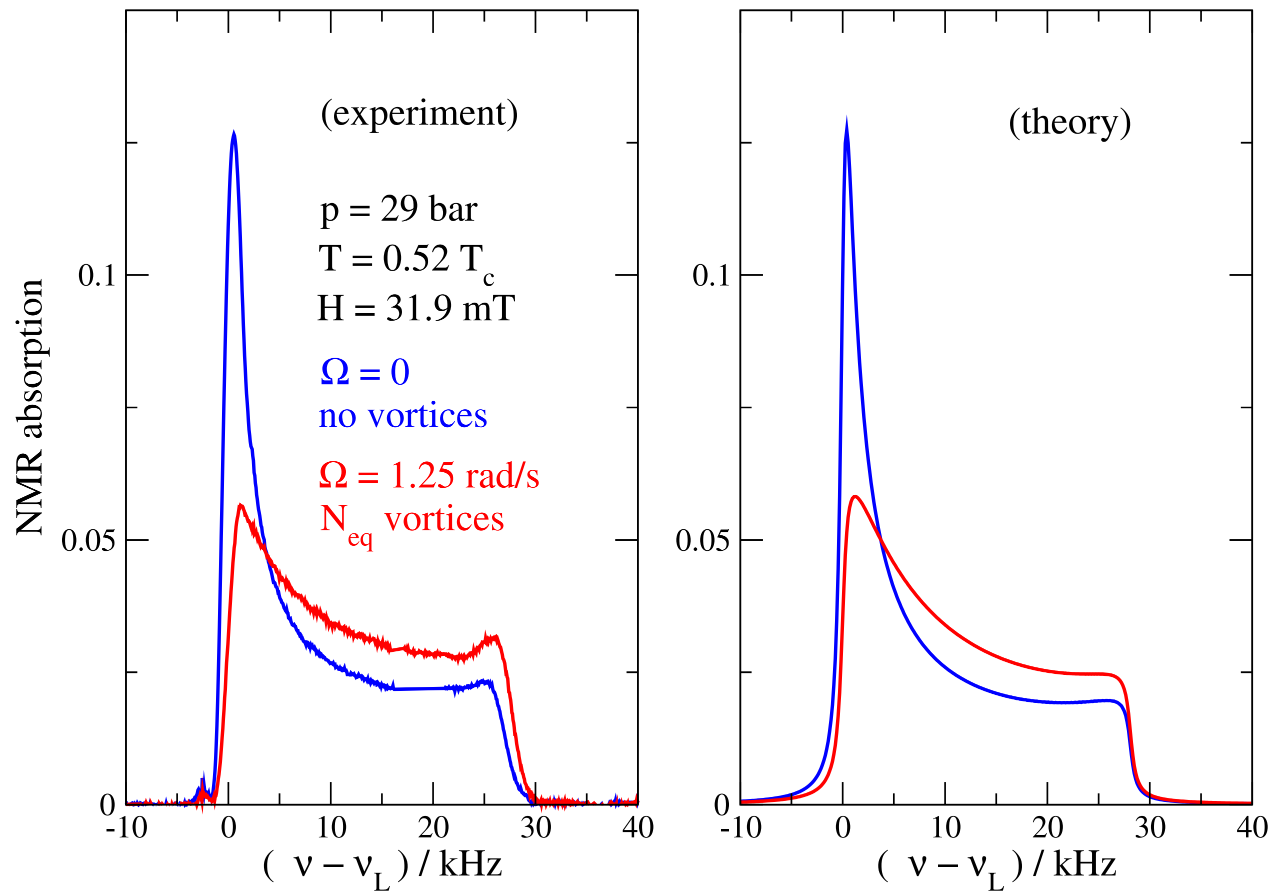
1. flow around the core
2. core



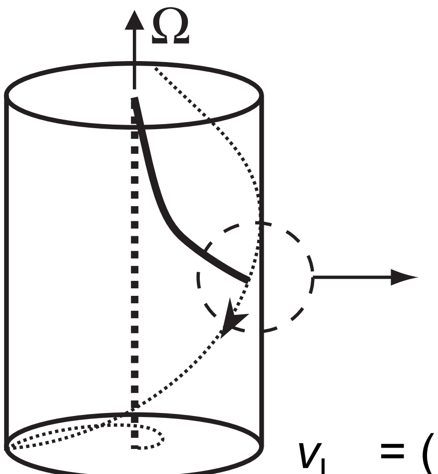



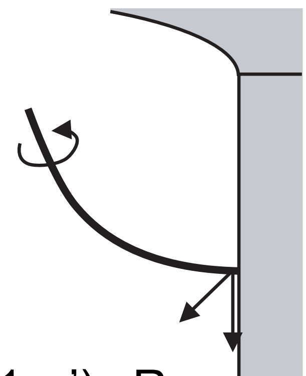
# Spectra: Experiment vs. Theory

- = 0 spectrum – no fitting parameters
- Equilibrium spectrum – λ fitted (in agreement with theoretical estimates)



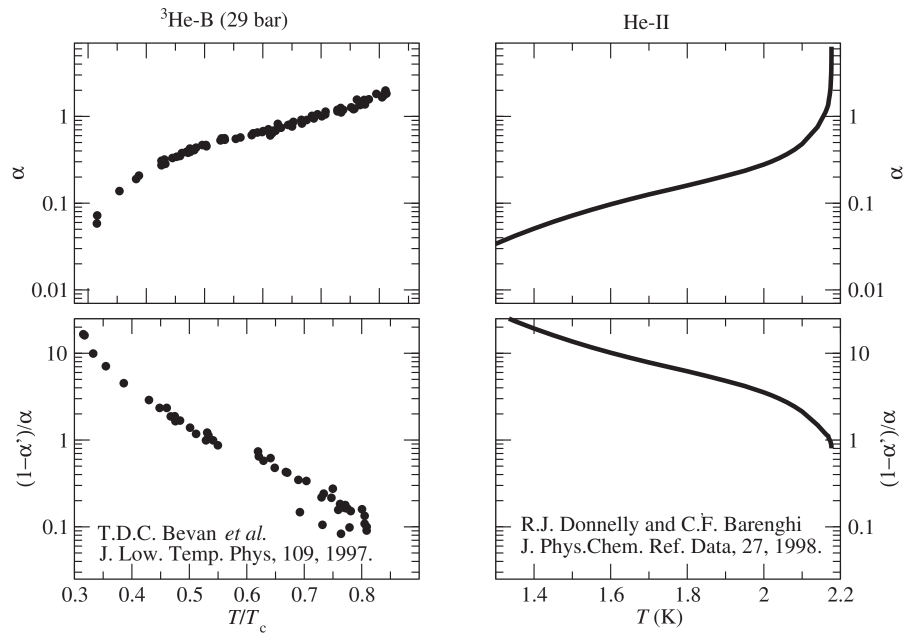
# Evolution of vortex lines in rotating flow



$v_{L,}$ = (1- ') R

$v_{L,z}$ = R




- dissipative mutual friction
- ' reactive mutual friction

# High temperatures ($T$ > 0.6 $T_c$)

High mutual friction damping:

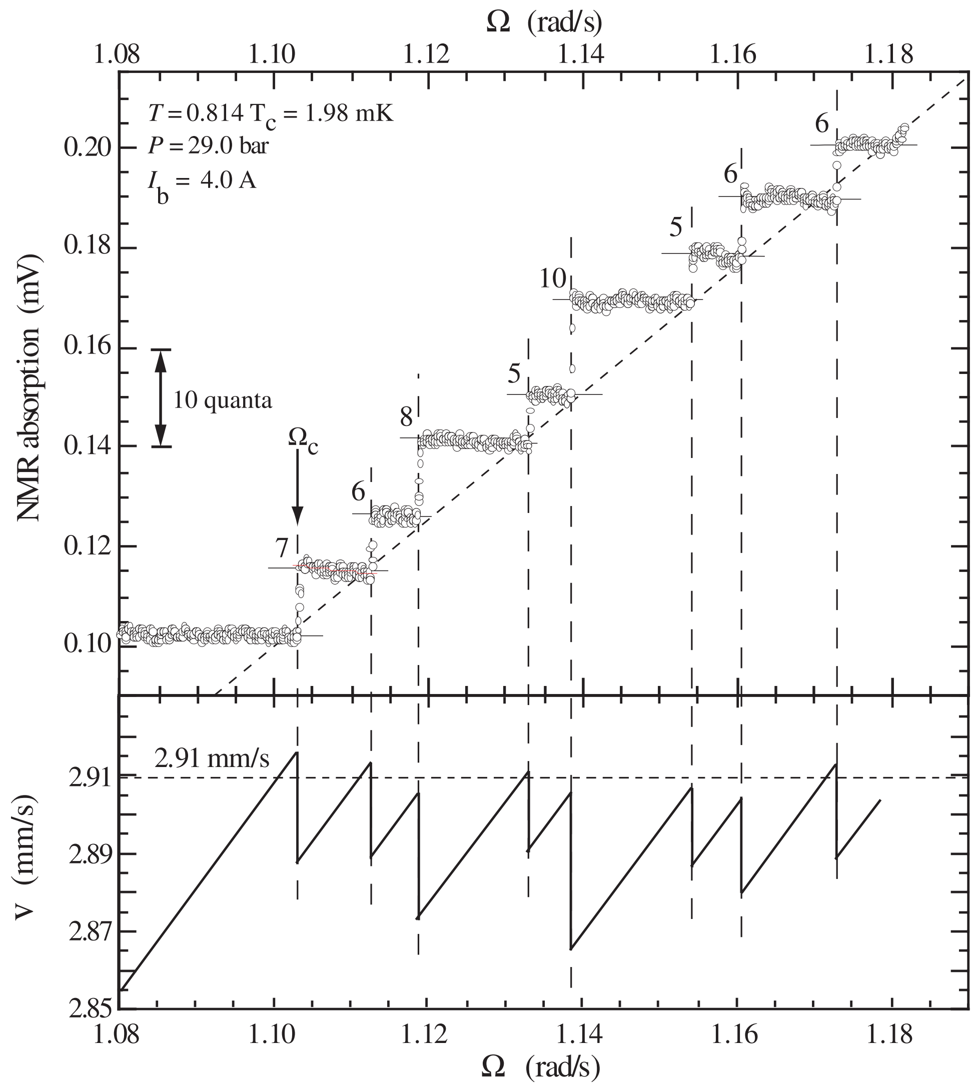
- Vortex lines move fast to become rectilinear lines
- Number of injected vortex loops = number of rectilinear vortex lines

Vortex number:

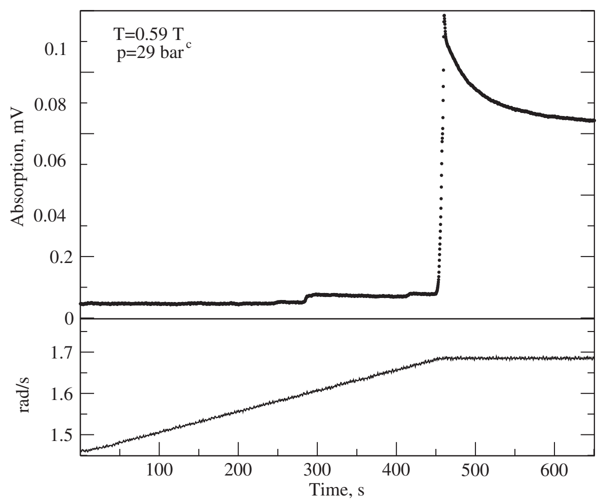
- Experimentally

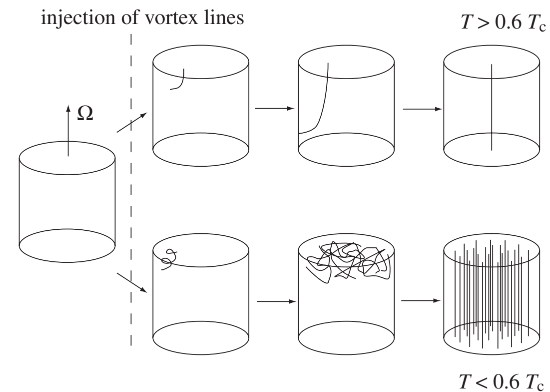
also

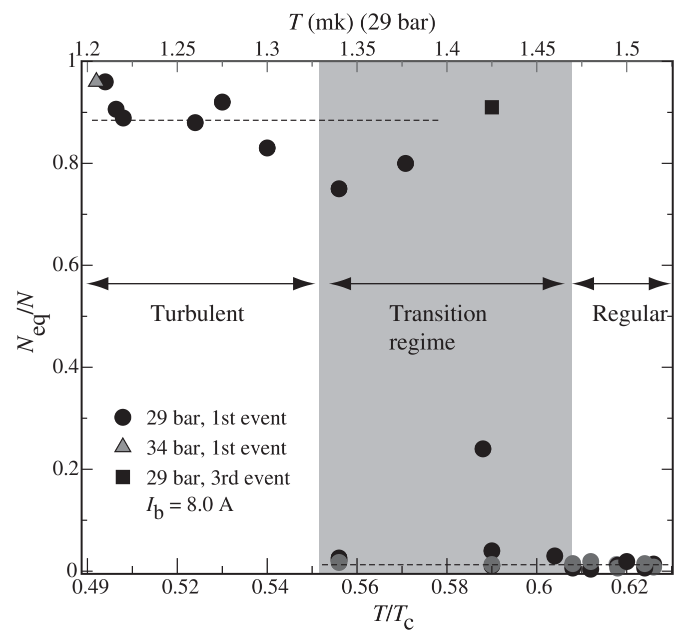
- Numerically by calculating spectrum



# Turbulent vortex dynamics: The transition

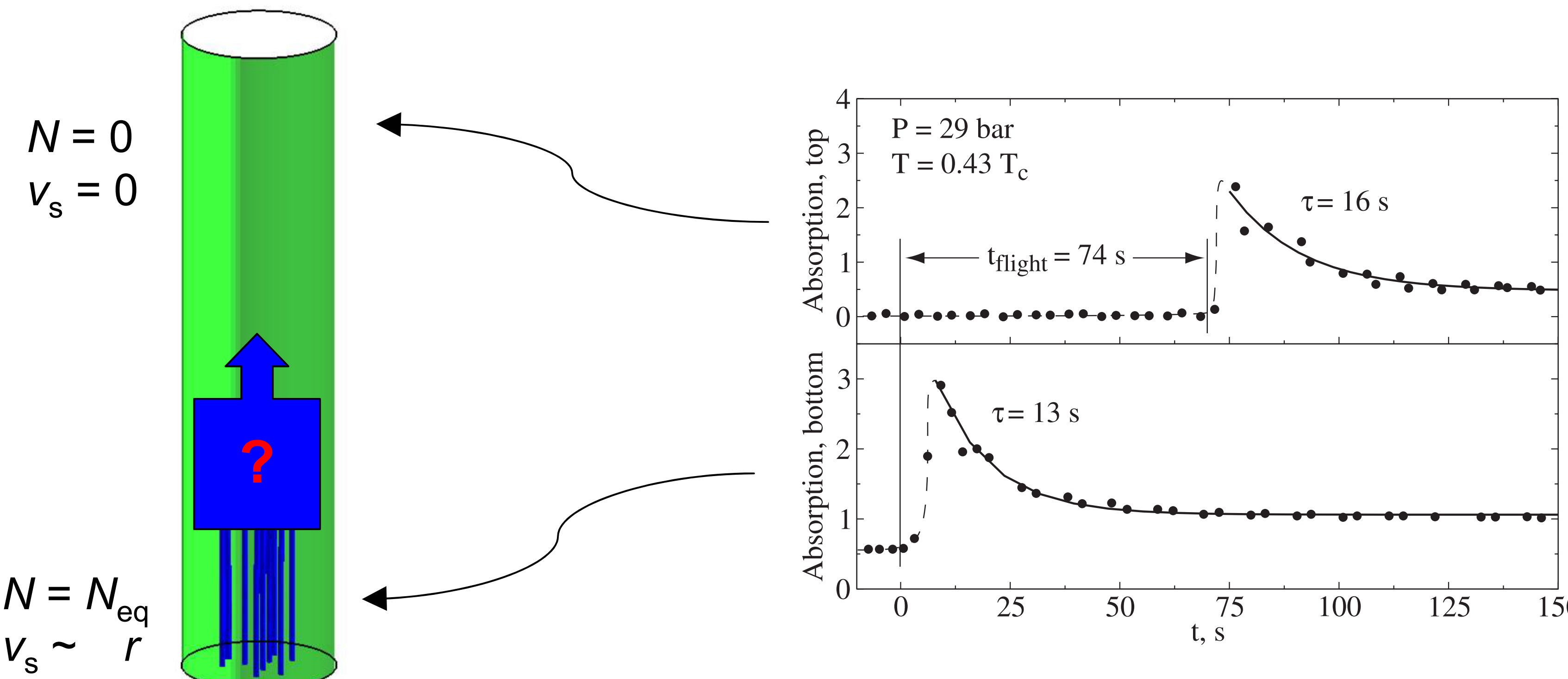


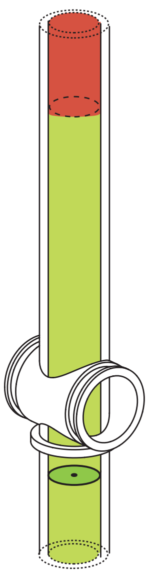



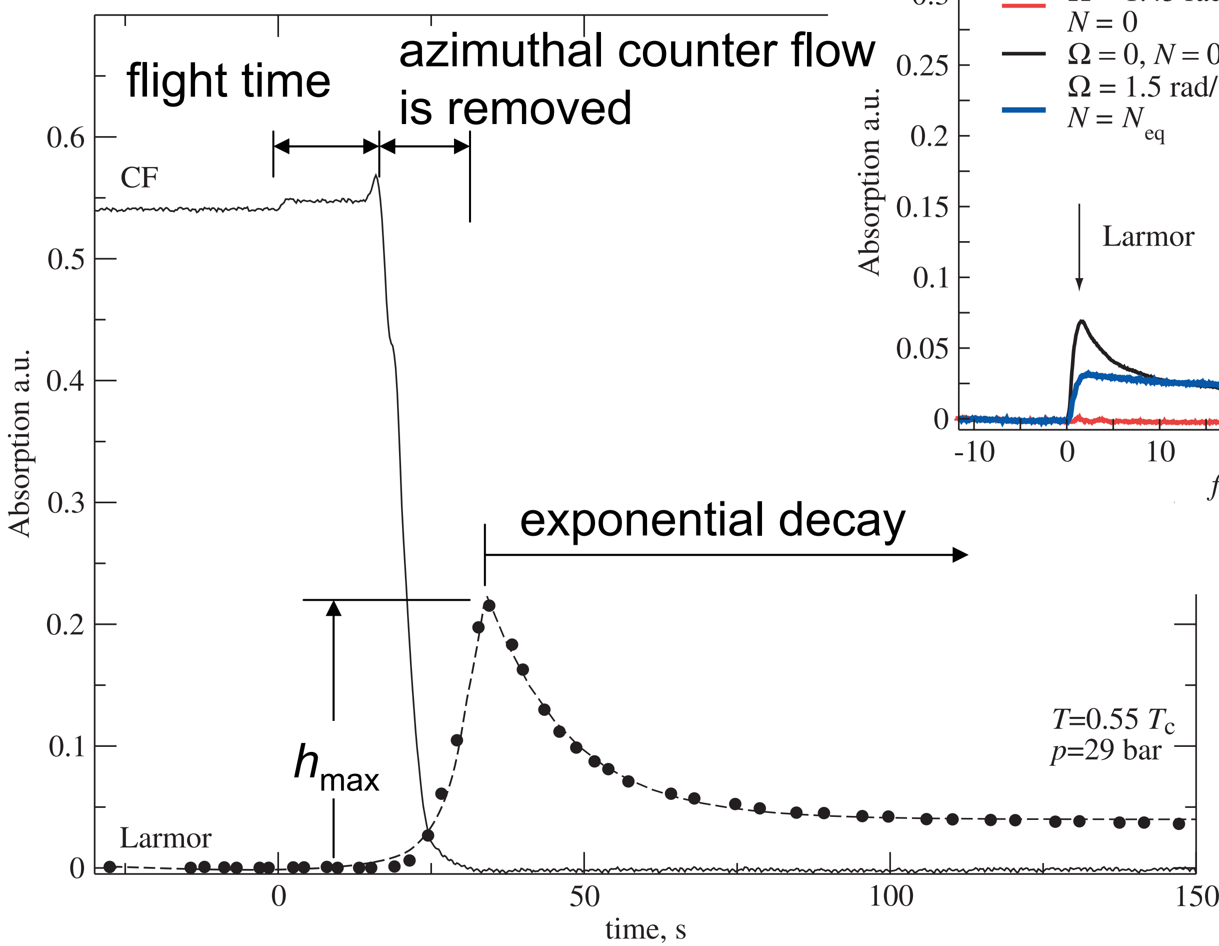

- Transition controlled by mutual friction
- Vortex number increases in a rapid burst
- Initial configuration affects the onset of the turbulent burst

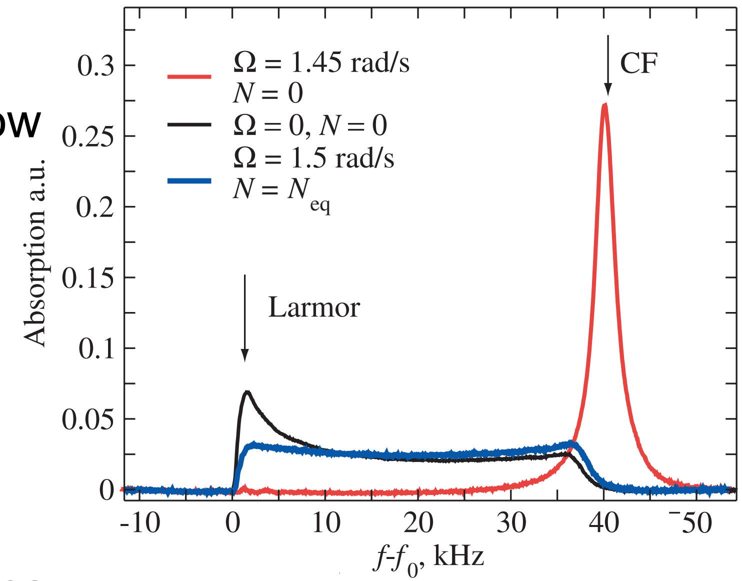
# Different experiment: How does the equilibrium number of vortex lines propagate into the vortex free region

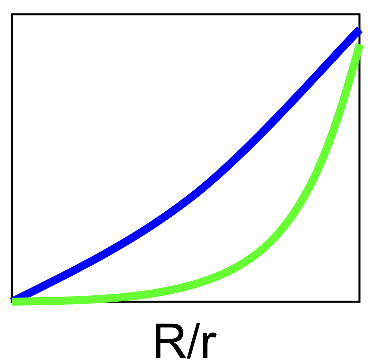


# NMR on superfluid ”spin-up”

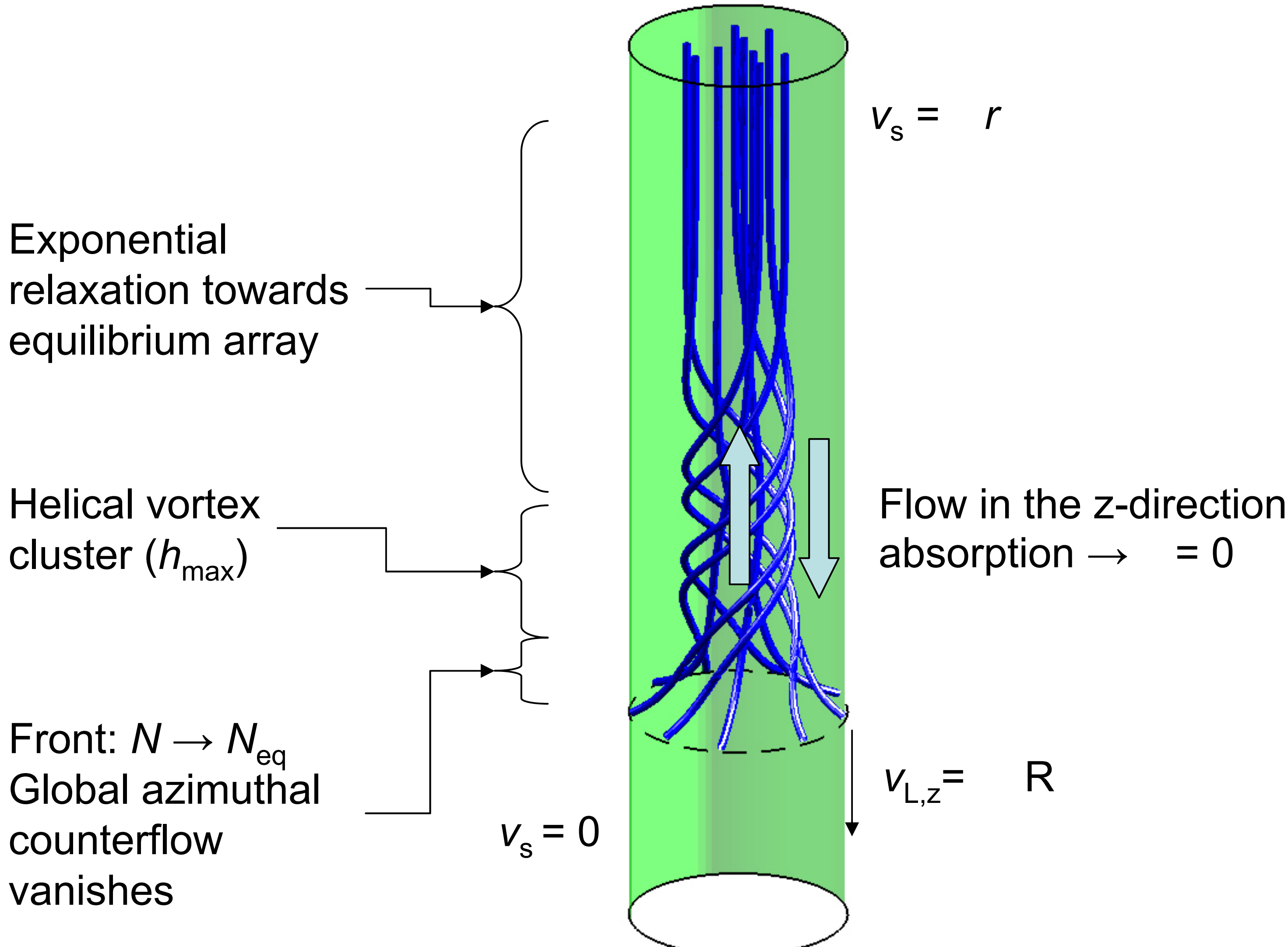




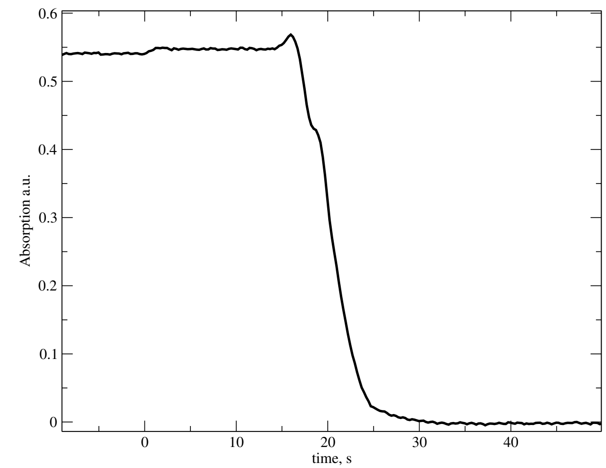



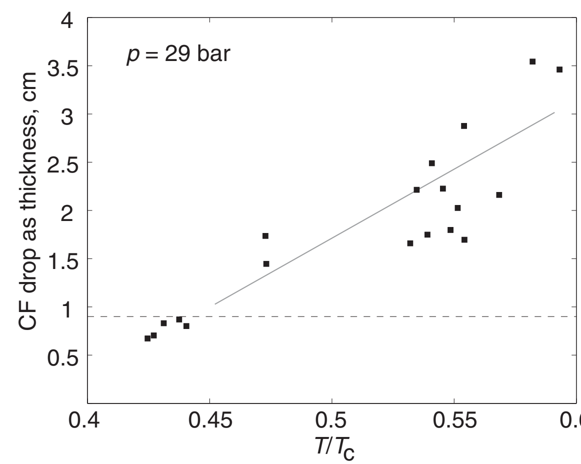
# Helical vortex state



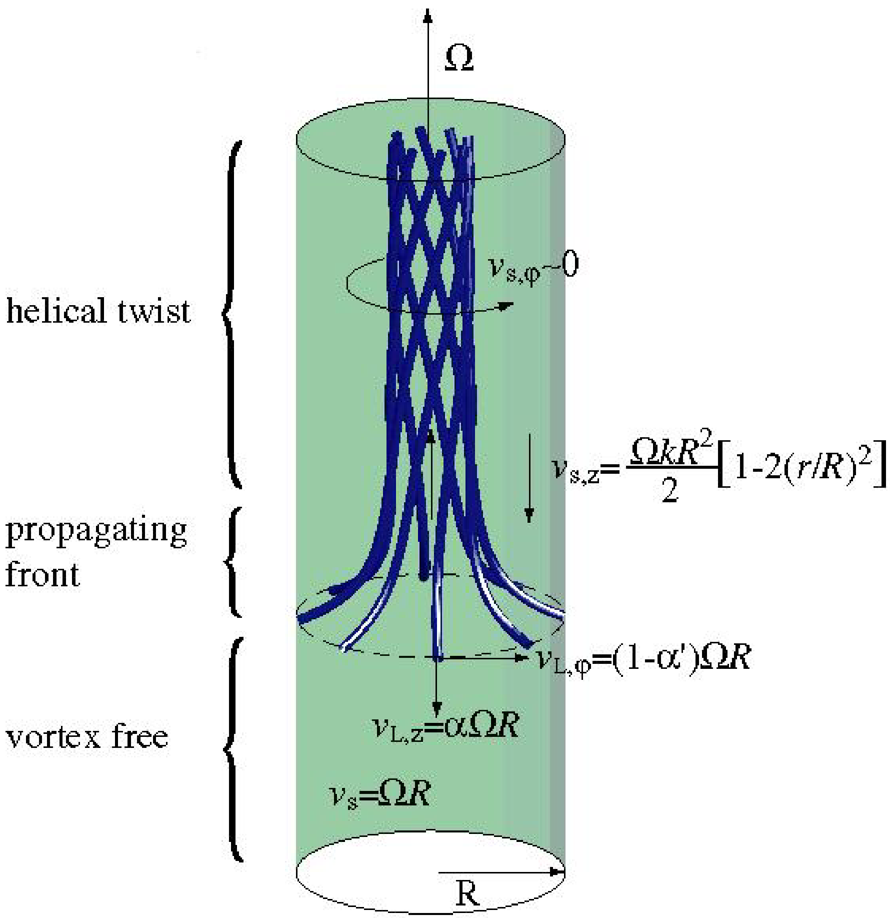
# The Front

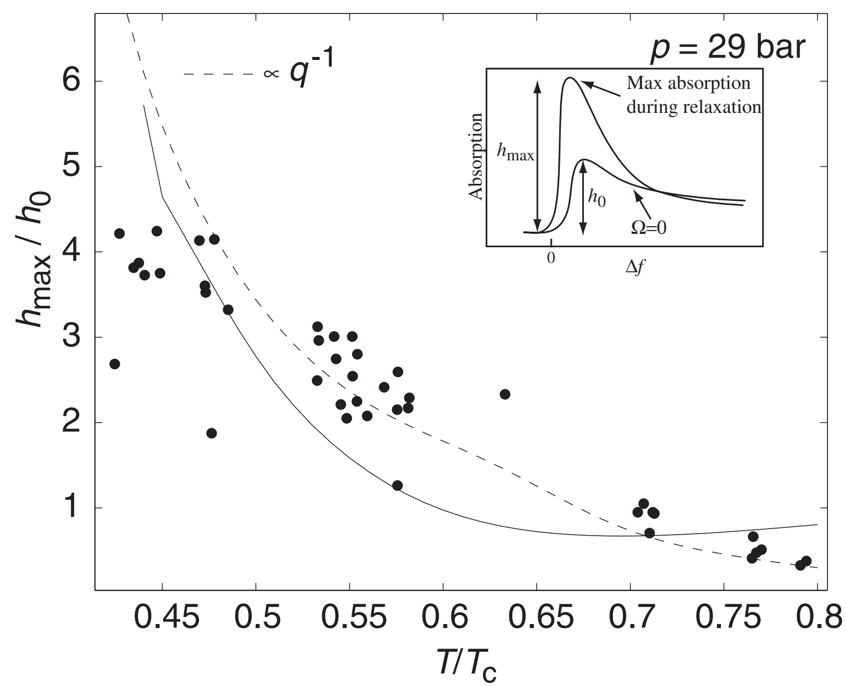
- NMR absorption at the counterflow peak ($\sin^2\beta$=0.8) is reduced
  - →Azimuthal counterflow vanishes
- The front becomes thinner with reducing temperature
- The thickness of the front does not dependend on



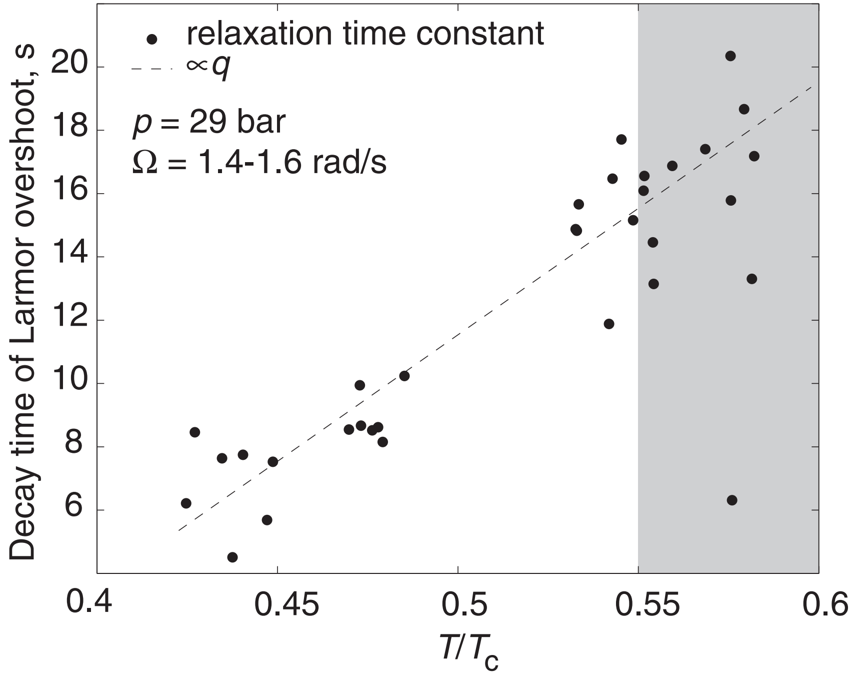
# Maximum Helix



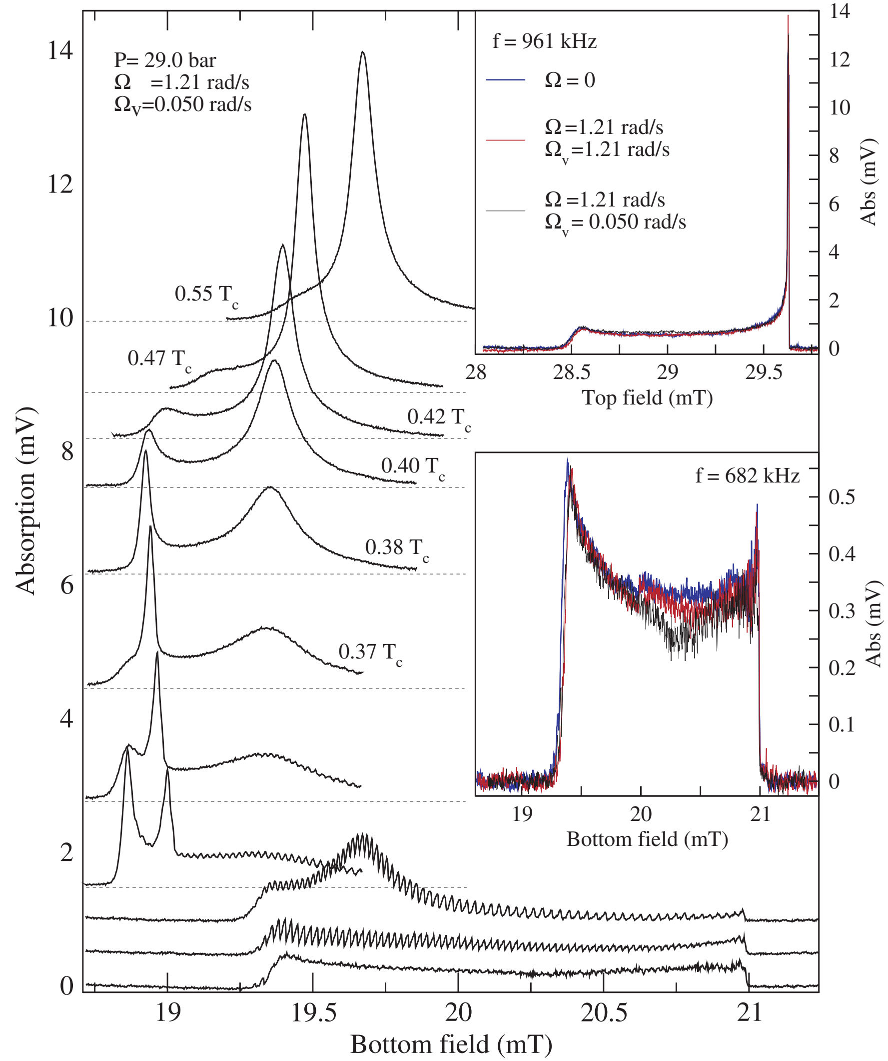
# Exponential Decay

- Decay becomes faster with reducing temperature
- Convective relaxation: $v_{s,z}$ assists in the decay of the helix



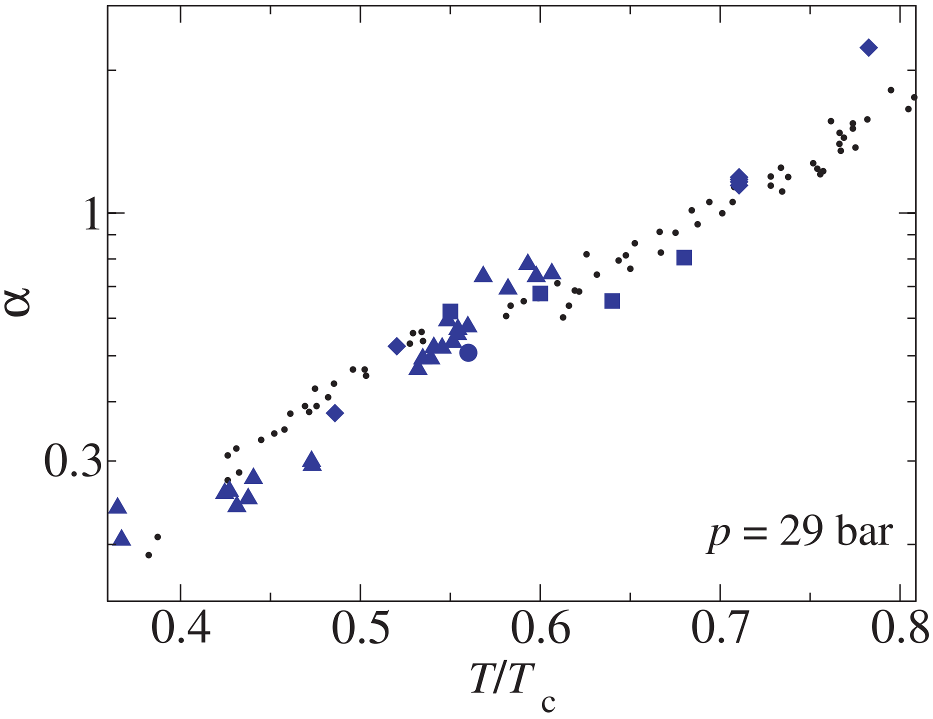
# Even lower temperatures ($T < 0.3\ T_c$)

- The effect of counterflow vanishes exponentially below ~$0.5\ T_c$
- These equilibrium state NMR techniques do not seem to work



# Time-of-flight measurement: the mutual friction parameter

- Measure the time a vortex line uses for travelling a known distance:
  → velocity
  → compare to $v_{L,z}$=     R
  →
- Various methods to perform the measurement



# Conclusions

- NMR provides a powerfull non-invasive method for counting vortex lines and their configuration.
- In rotating $^3$He-B:
  - T>0.6 Tc: Dynamics of single vortex lines
  - T<0.6 Tc: Vortex number tends to increase to $N_{eq}$, collective effects
  - The presence of turbulence concluded indirectly