VORTEX FORMATION IN NEUTRON-IRRADIATED ^{3}He-B FLOW

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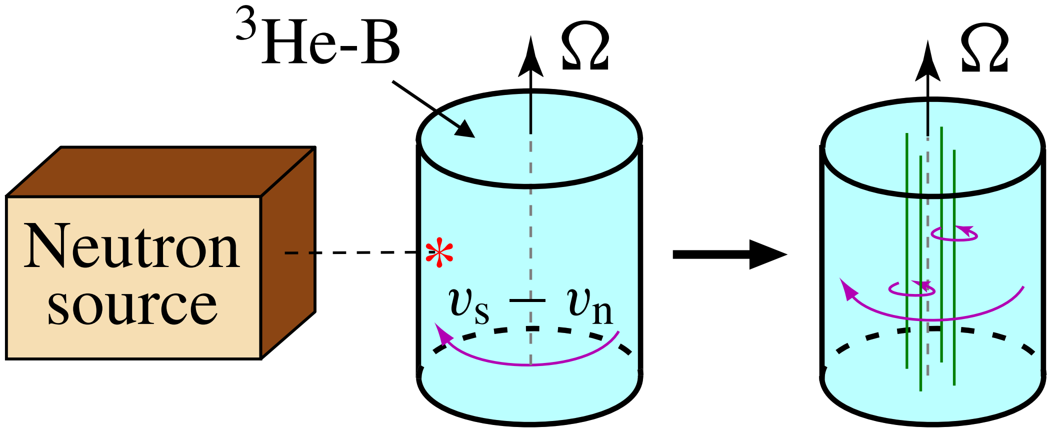
ROTA

TALK OVERVIEW

1. Observation of neutron induced vortex formation in rotating ^{3}He-B.



V.M.H. Ruutu *et al.*:

$P = 2 - 21$ bar

$T > 0.8\, T_c$

Properties and interpretation.

2. Recent measurements at $P = 10$ and 29 bar and $T \approx 0.5\, T_c$.

New features: a) Suppression of vortex formation.

b) Turbulence triggered by neutron absorption.

A ^{3}He-B primer: Disorder and topological defects appear from “nothing”.

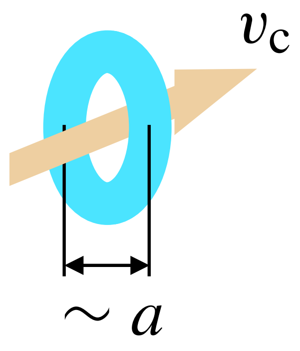
METASTABLE ROTATION AND VORTEX FORMATION

Vortex lines are favourable at $\Omega > \Omega_{c1} \sim 10^{-2}$ rad/s (sample $R \sim$ few mm).

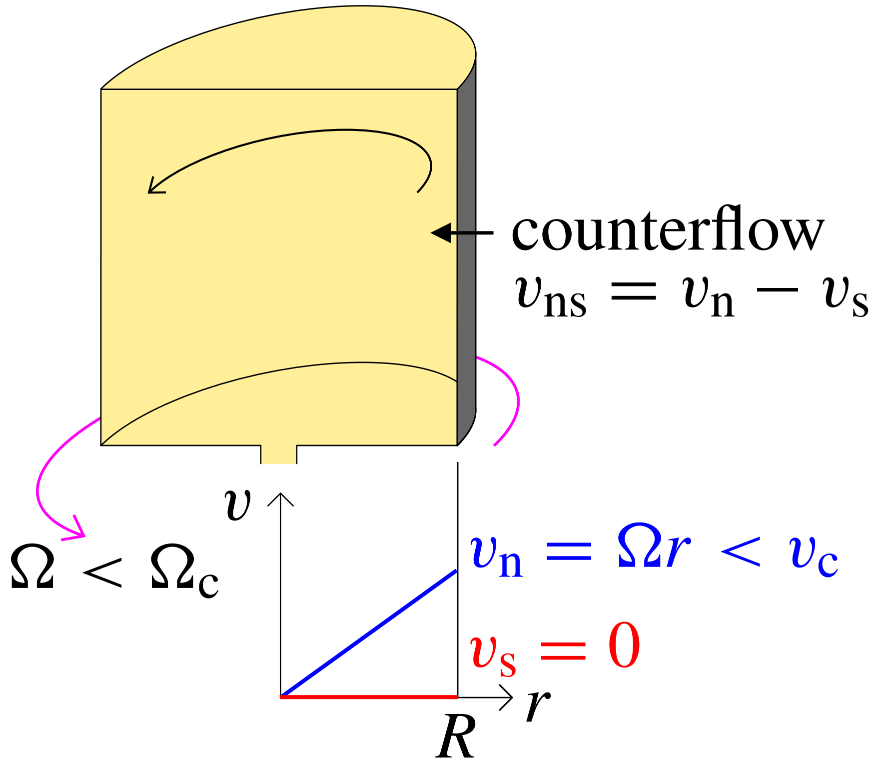
In superfluid ^{3}He-B metastable vortex-free rotation at $\Omega \gg \Omega_{c1}$:

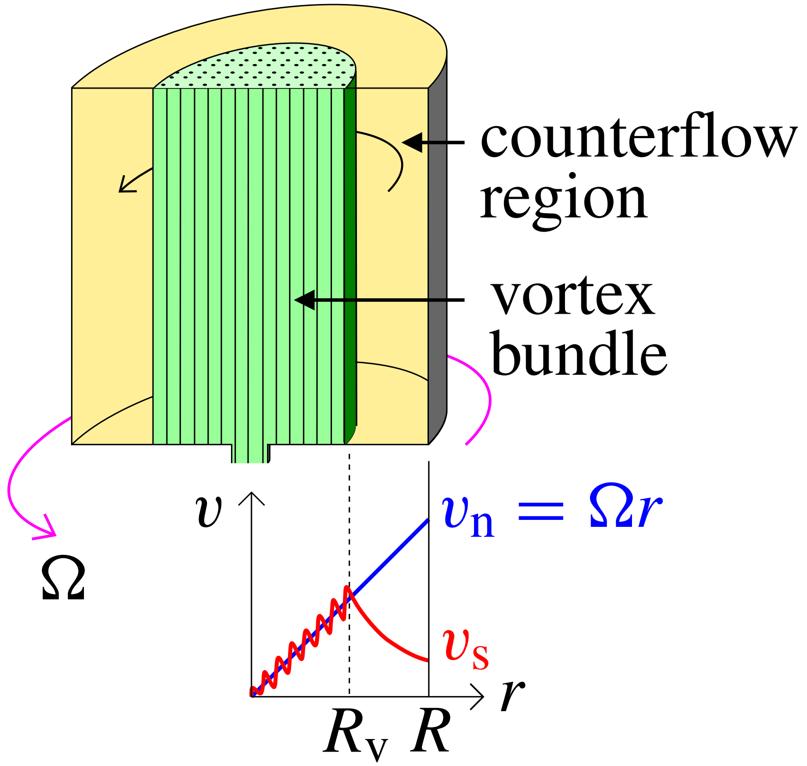
- clean
- no remnant vortices (core size $a >$ wall roughness)
- barrier $E_v \sim \rho_s \kappa^2 a > 10^5 k_B T$ inhibits vortex formation

$\Rightarrow$ vortex formation can be studied in a controlled way.



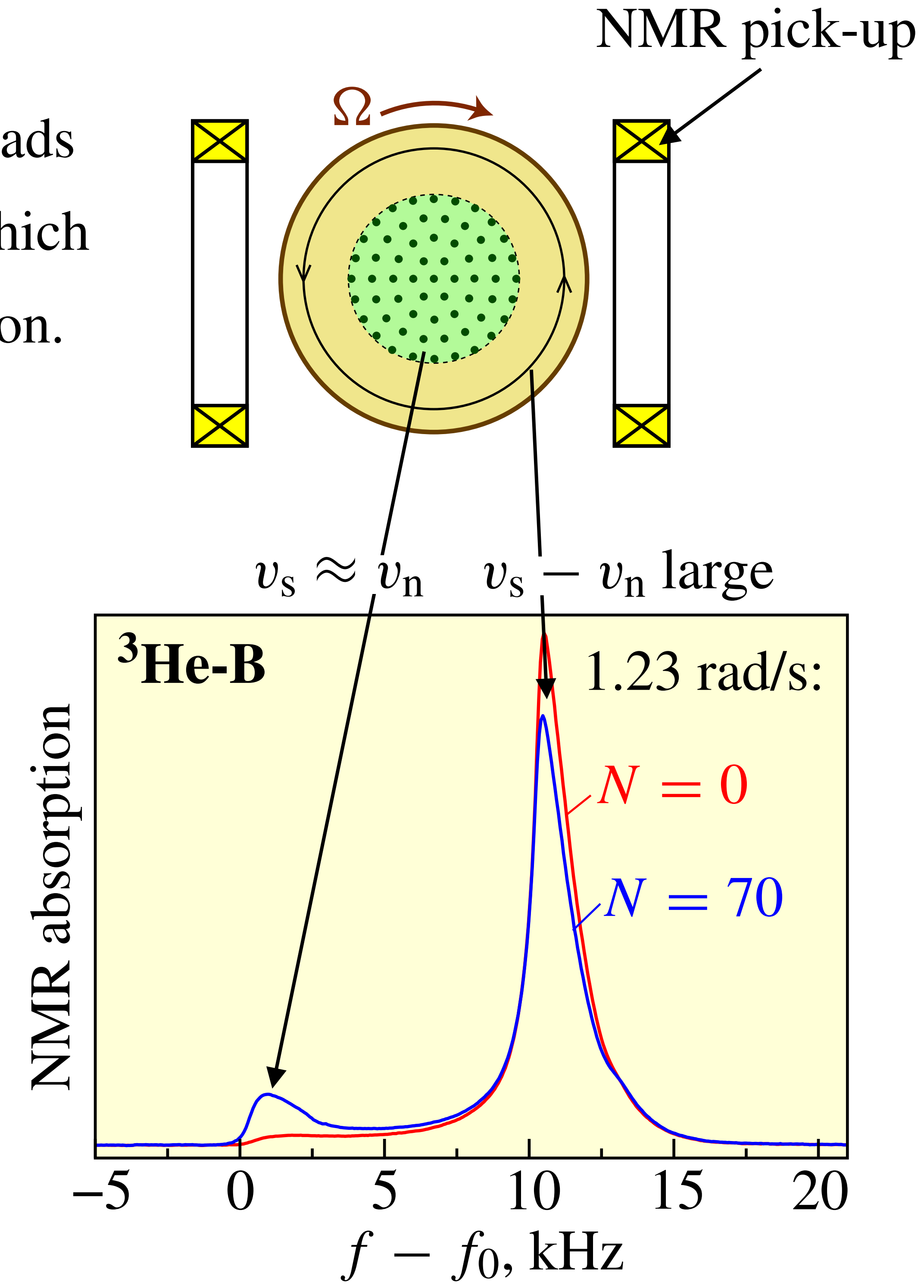
Bulk flow instability: $E_v \sim \rho_s v_c^2 a^3$. In ^{3}He-B $v_c \gtrsim 1\,\mathrm{cm/s}$.





NMR: A TOOL TO OBSERVE VORTICES

Spin-orbit interaction in Cooper pairs leads to frequency shift in NMR precession which depends on order parameter configuration.



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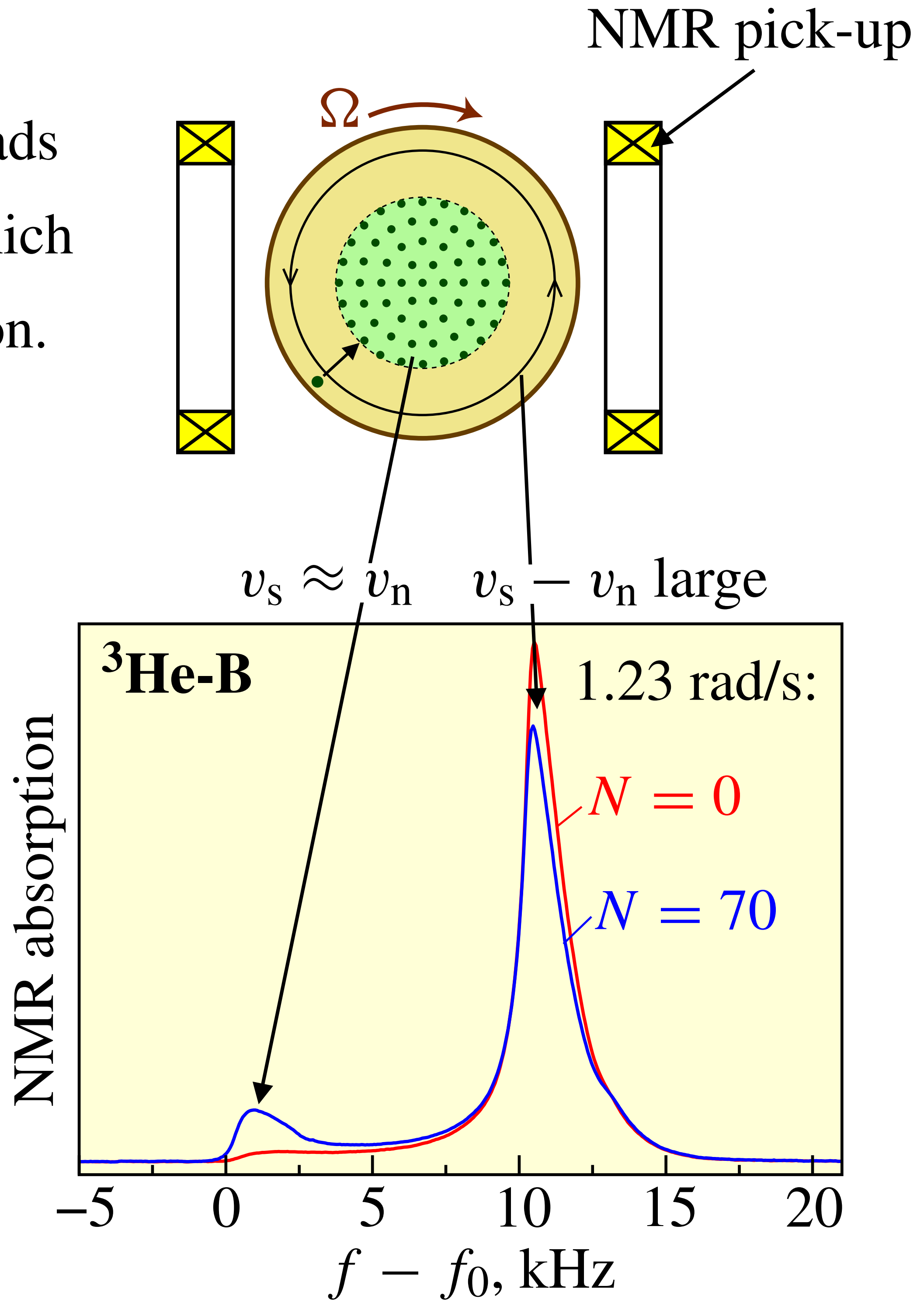
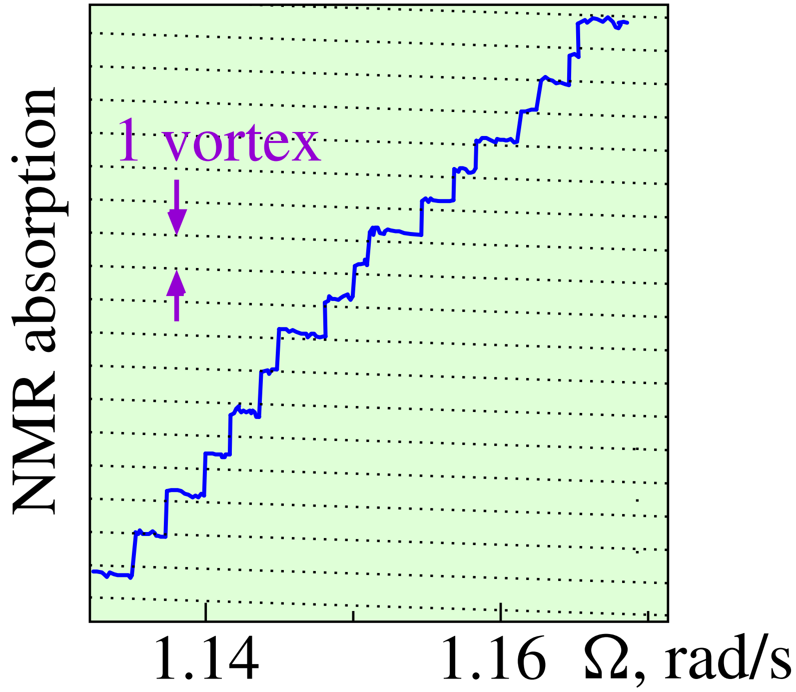
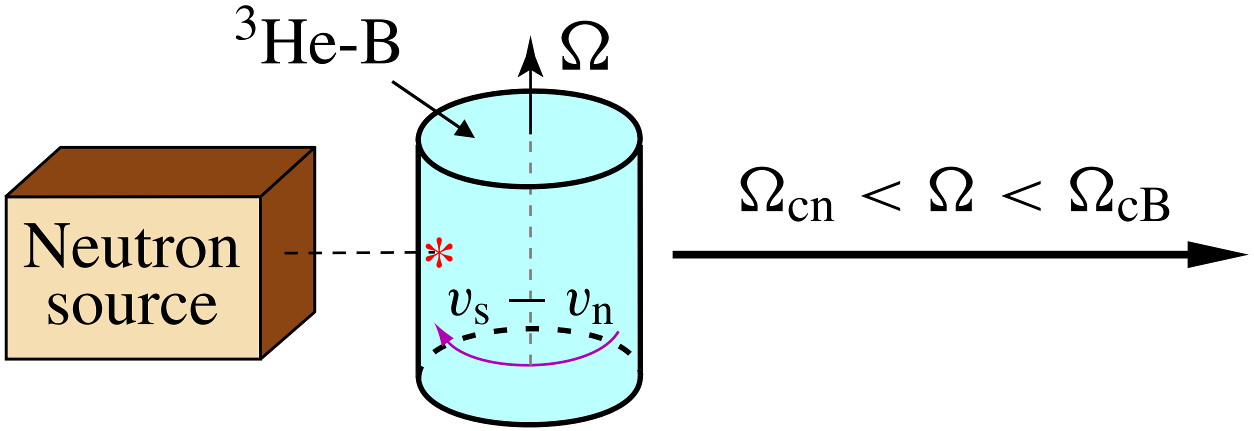
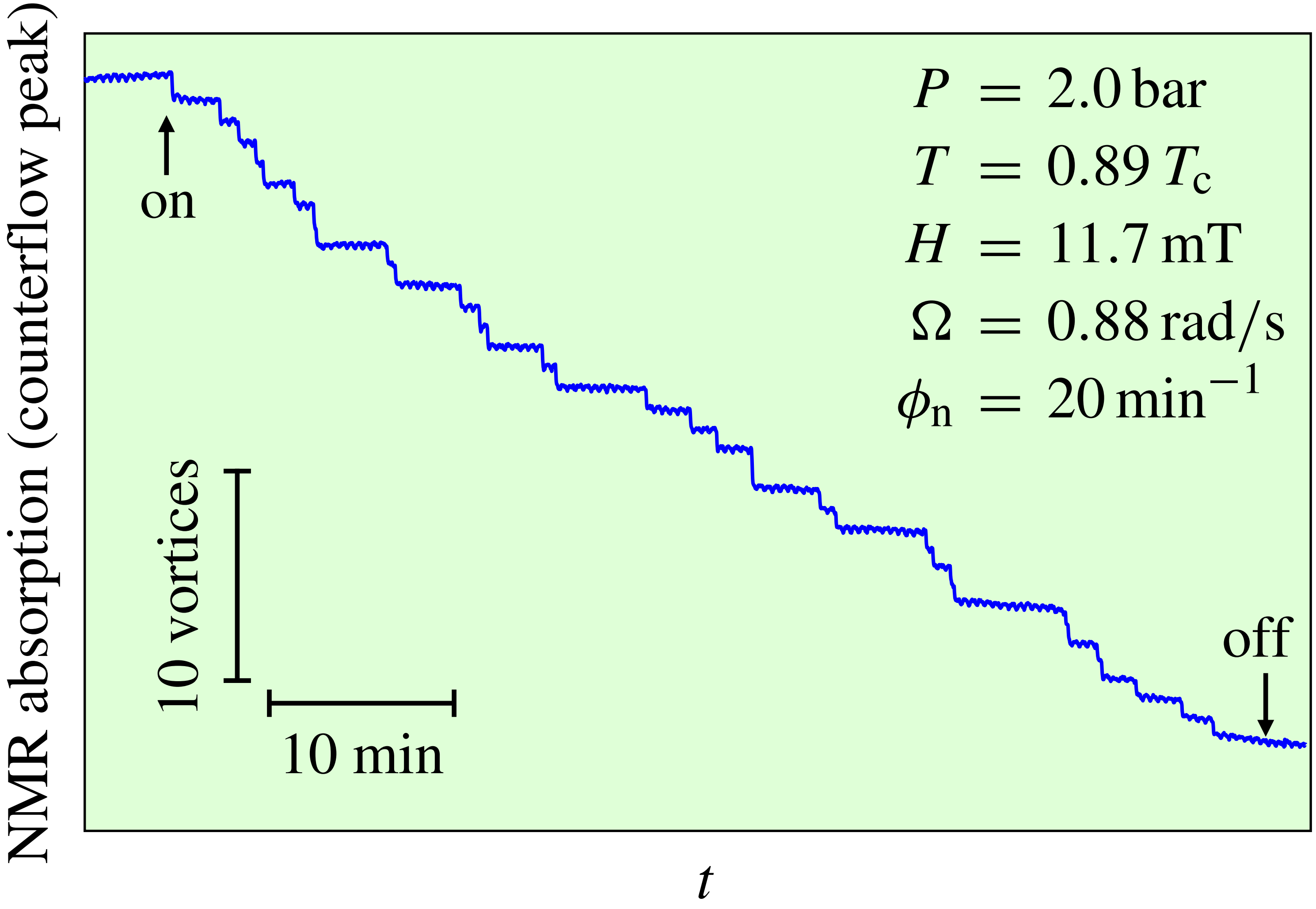


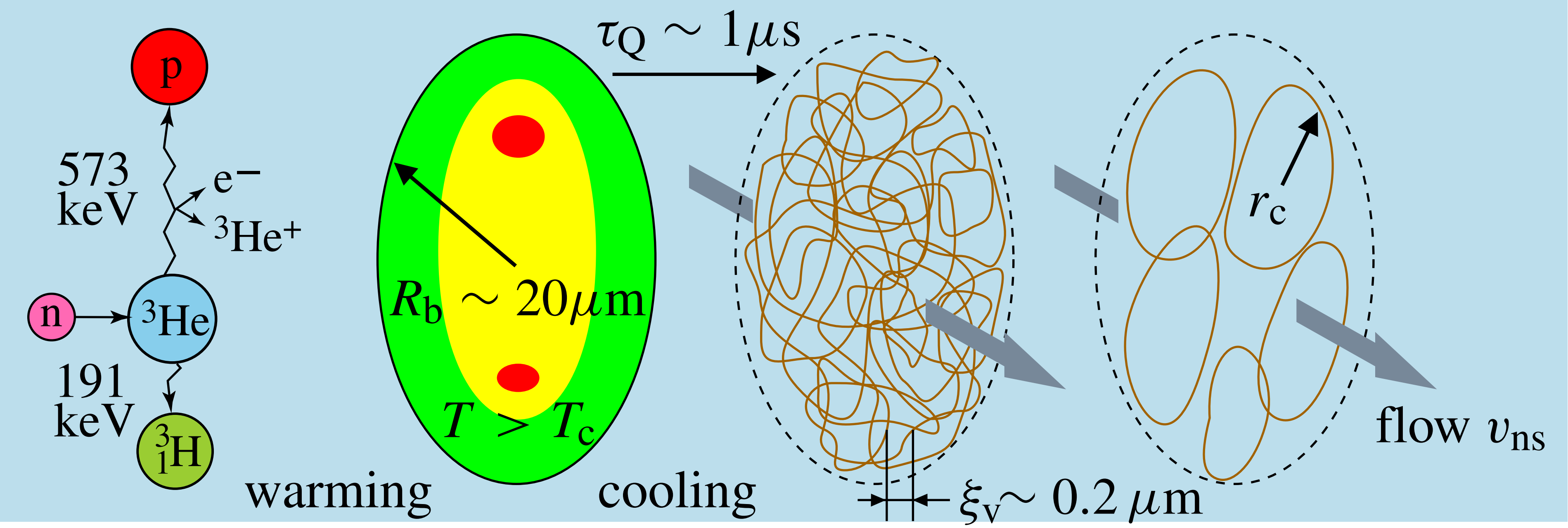


VORTEX FORMATION TRIGGERED BY NEUTRON ABSORPTION





INTERPRETATION OF VORTEX FORMATION

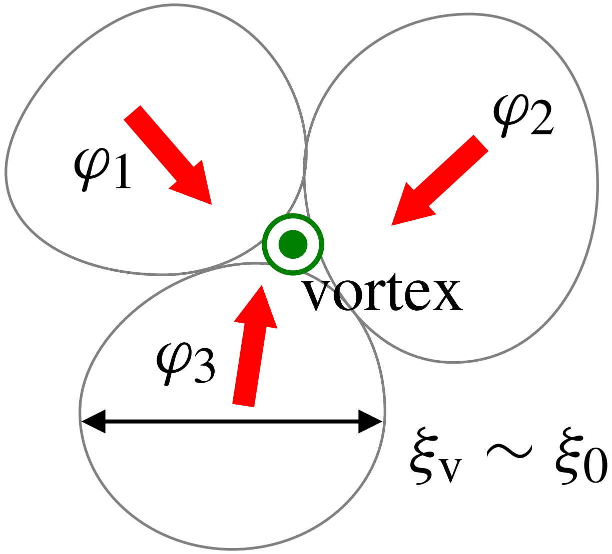


Kibble-Zurek mechanism:

Broken simmetry at $T < T_c$

+ Critical slowing down:

$$\tau(T) = \tau_0(1 - T/T_c)^{-1}$$

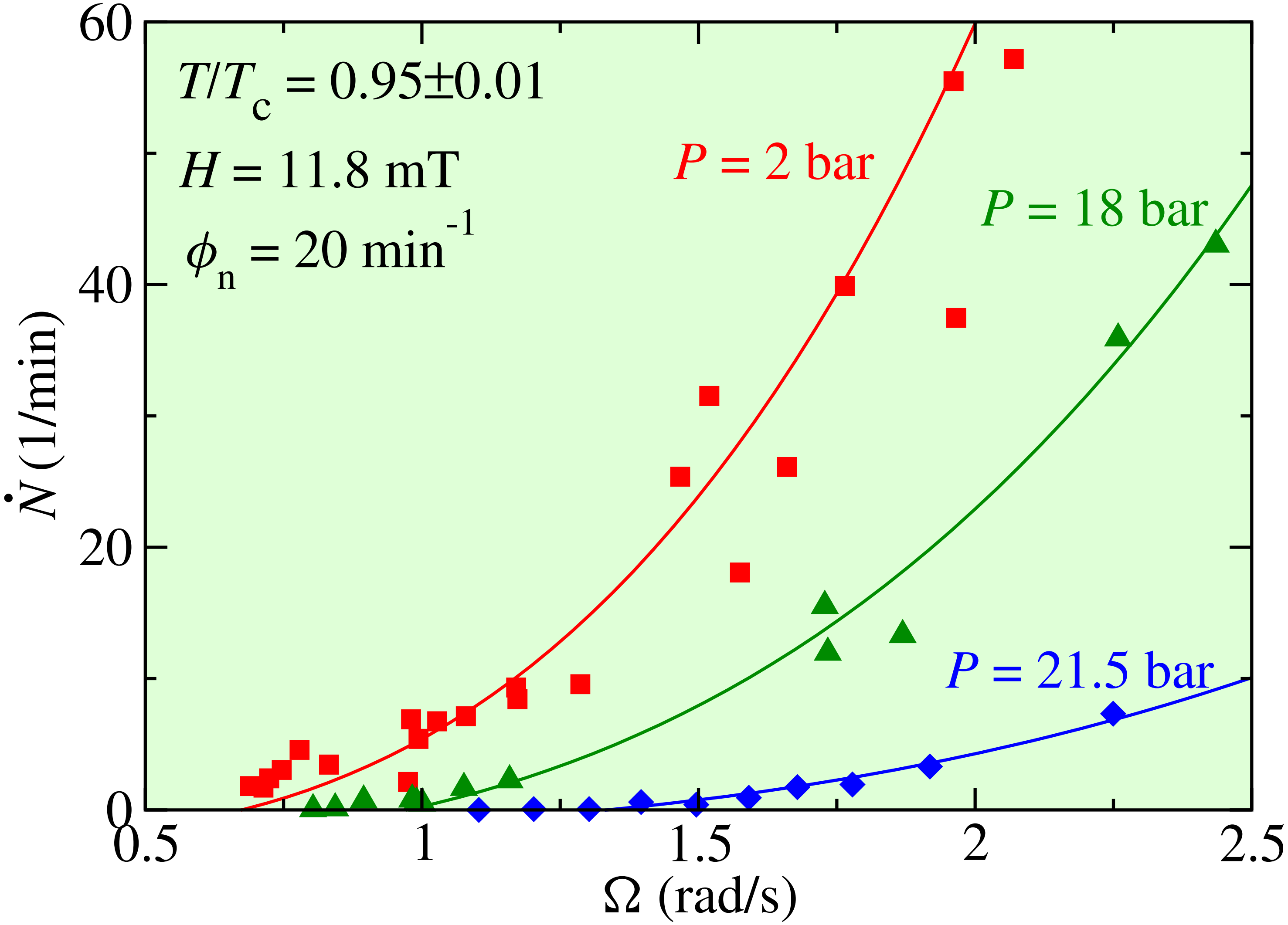


$$\xi_v \sim \xi_0(\tau_Q/\tau_0)^{1/4}$$

VORTEX FORMATION RATE

Studied dependence on:

- neutron flux $\phi_n = 0 \div 20\,\mathrm{min}^{-1}$
- temperature $T = 0.78 \div 0.98 T_c$
- pressure $P = 2 \div 21.5\,\mathrm{bar}$
- magnetic field $H = 0 \div 60\,\mathrm{mT}$
- rotation Ω and number of vortex lines N (i.e. on $v_n = \Omega R$, $v_s = \kappa N / 2\pi R$)



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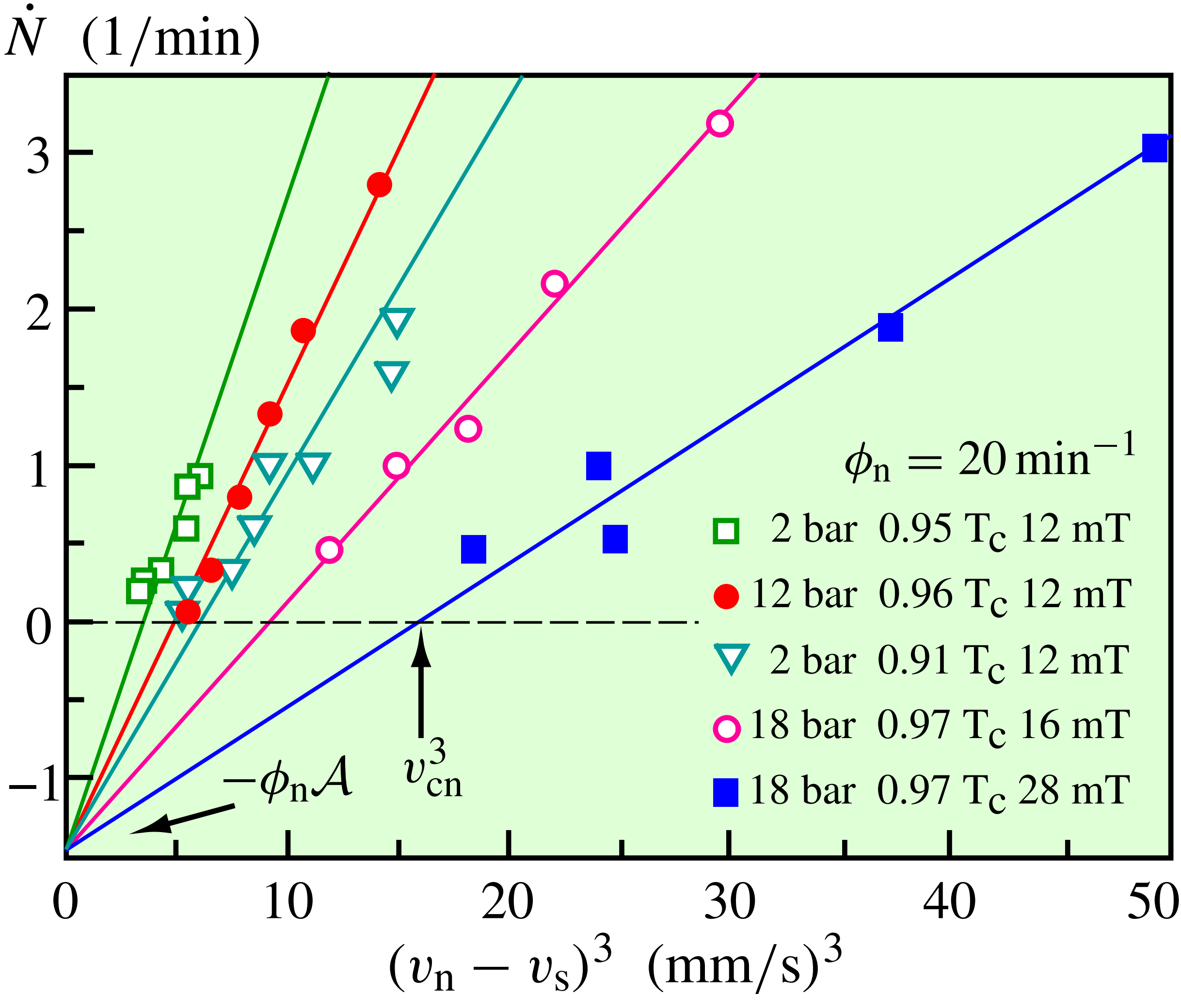
- rotation Ω and number of vortex lines N (i.e. on $v_\mathrm{n} = \Omega R$, $v_\mathrm{s} = \kappa N / 2\pi R$)

Result:

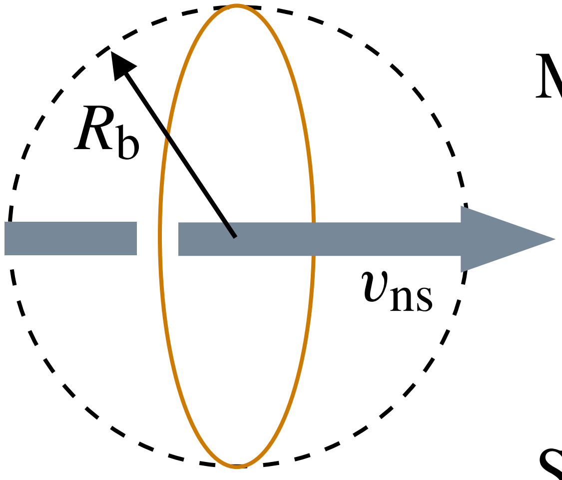
$$\frac{dN}{dt} = \phi_\mathrm{n} \underset{\uparrow}{\mathcal{A}} \left[\left(\frac{v_\mathrm{n} - v_\mathrm{s}}{v_\mathrm{cn}(T, P, H)} \right)^3 - 1 \right]$$

universal number = 0.07



THRESHOLD VELOCITY

Vortex ring expands if $r > r_\mathrm{c}(v_\mathrm{ns}) = \dfrac{\kappa}{4\pi v_\mathrm{ns}} \ln\left(\dfrac{r_\mathrm{c}}{\xi(T,P)}\right)$



Minimum $v_\mathrm{ns} \Rightarrow$ maximum size $\Rightarrow r_\mathrm{c}(v_\mathrm{cn}) \sim R_\mathrm{b}$

$$v_\mathrm{cn} \propto \frac{1}{R_\mathrm{b}} \ln(R_\mathrm{b}/\xi)$$

Simple diffusion model: $R_\mathrm{b} = \sqrt{\dfrac{3}{2\pi e}} \left[\dfrac{E_0}{C\,(T_\mathrm{c} - T)}\right]^{1/3}$

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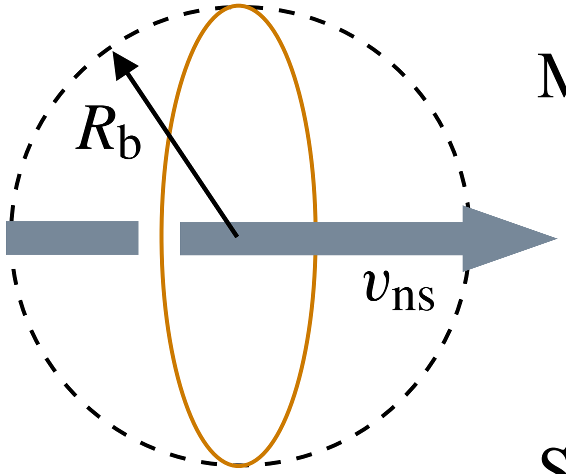

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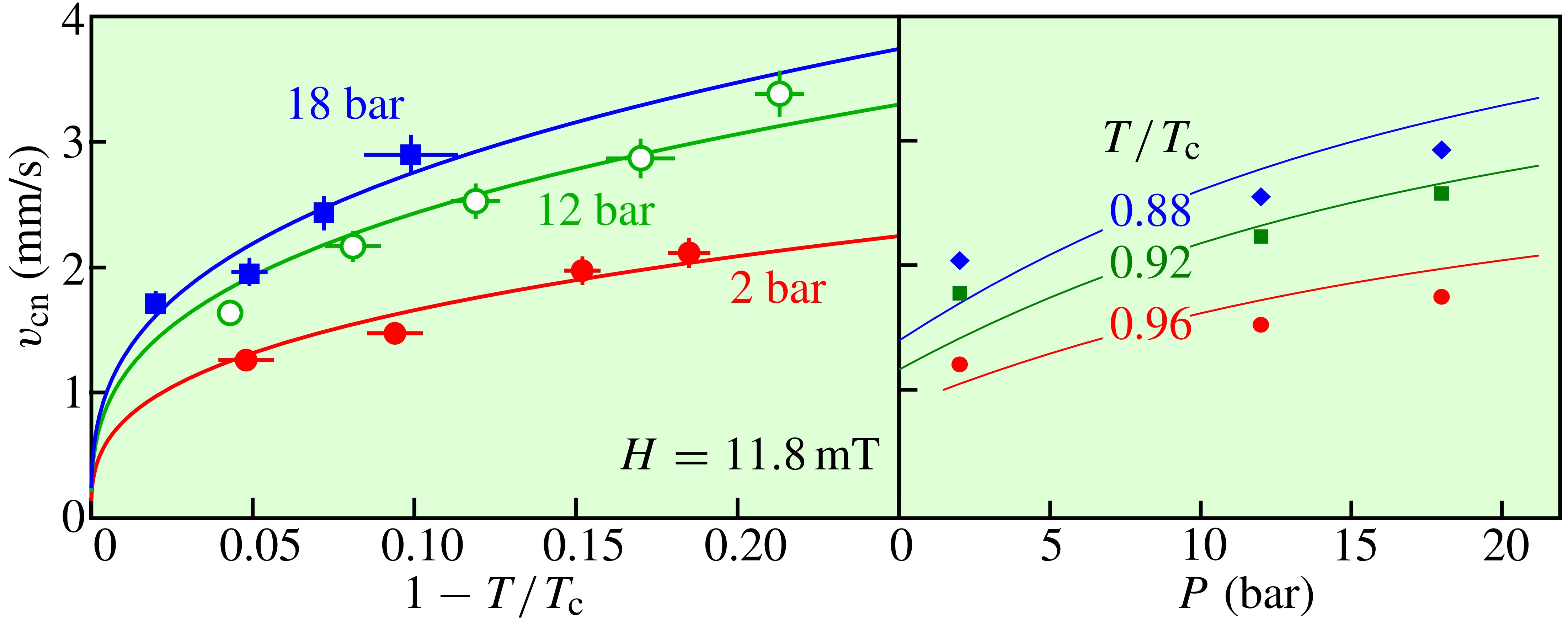
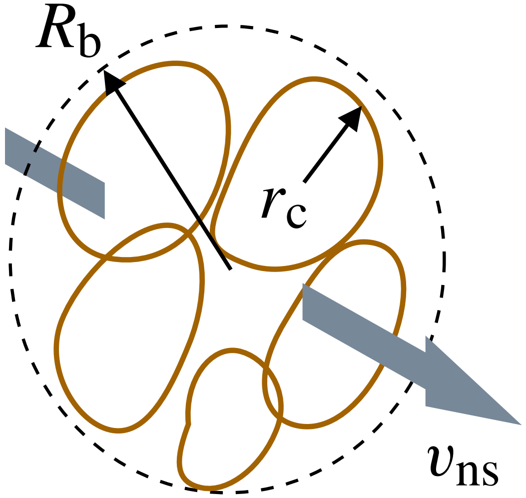


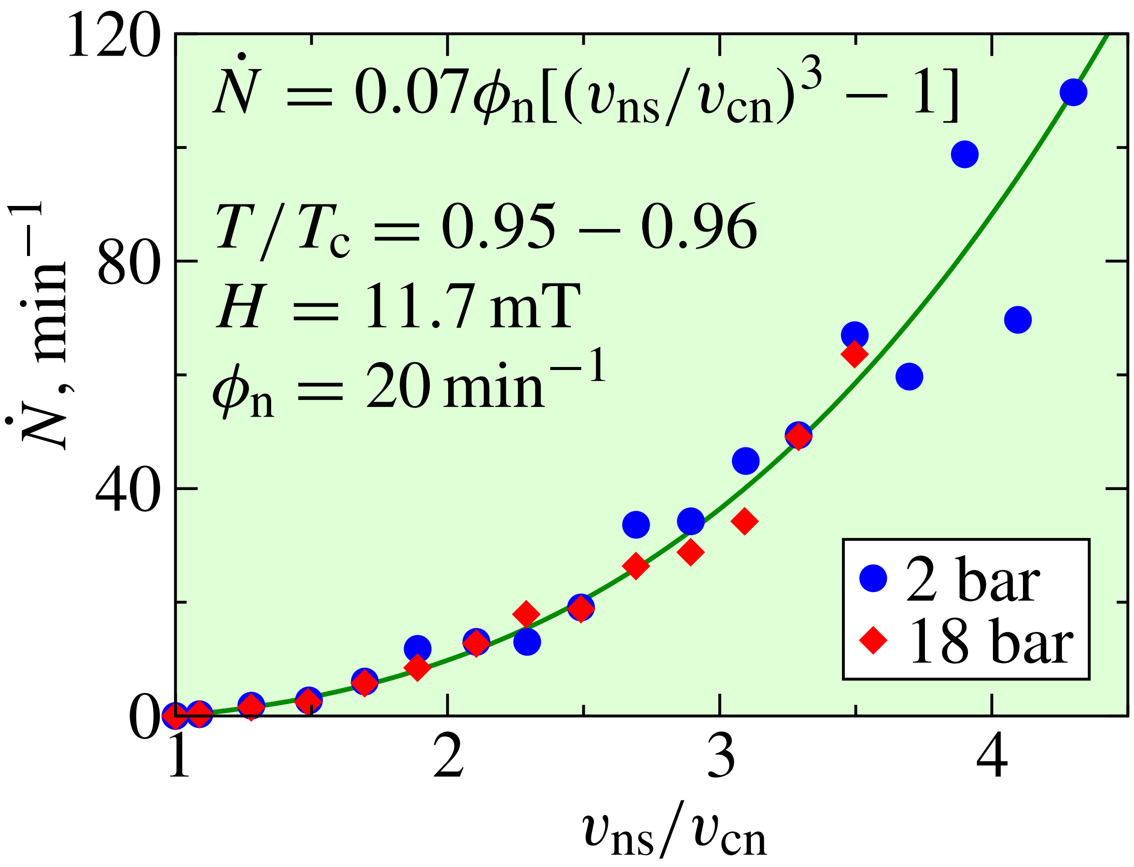
VELOCITY DEPENDENCE OF VORTEX VORMATION RATE



Cubic dependence of $\dot{N}$ on $v_\mathrm{ns}/v_\mathrm{cn}$ means that vortices are exctracted from the whole **volume** of the “bubble”:

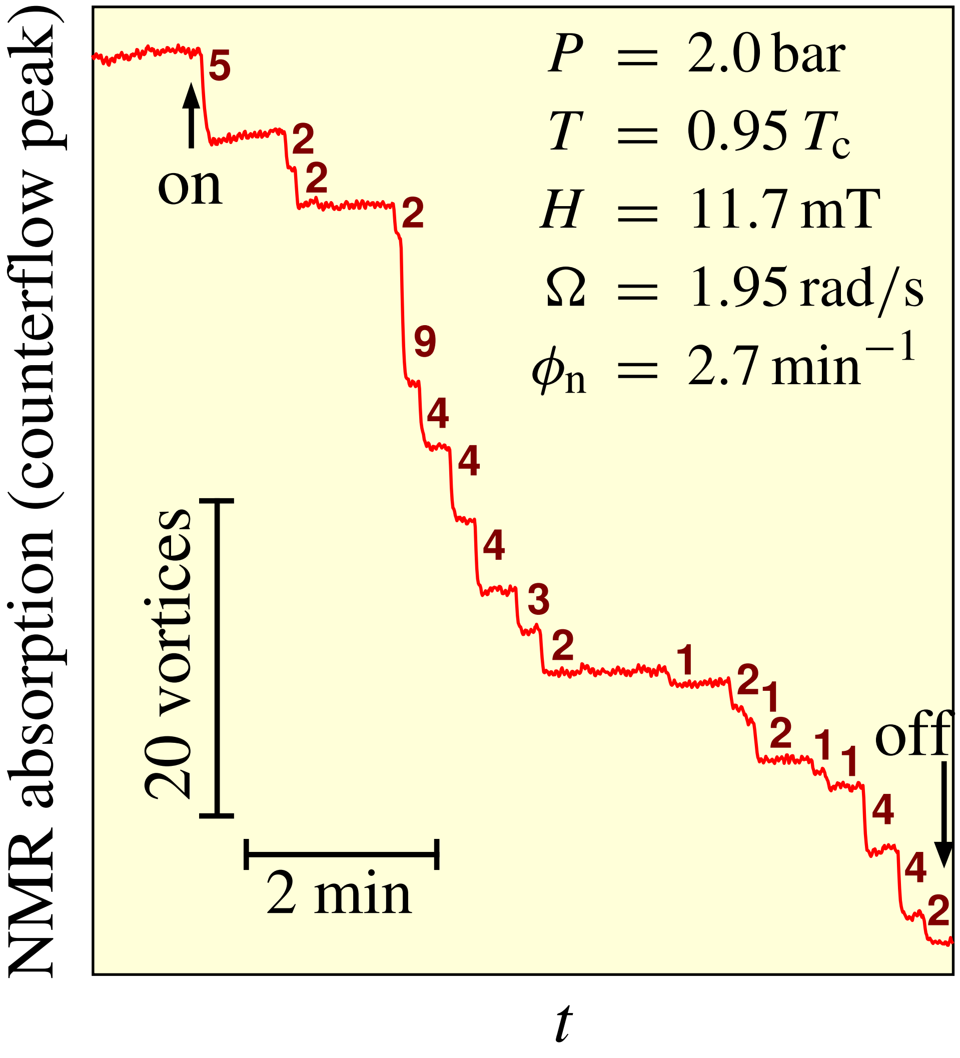
$$\dot{N}/\phi_\mathrm{n} \sim (R_\mathrm{b}/r_\mathrm{c})^3,$$

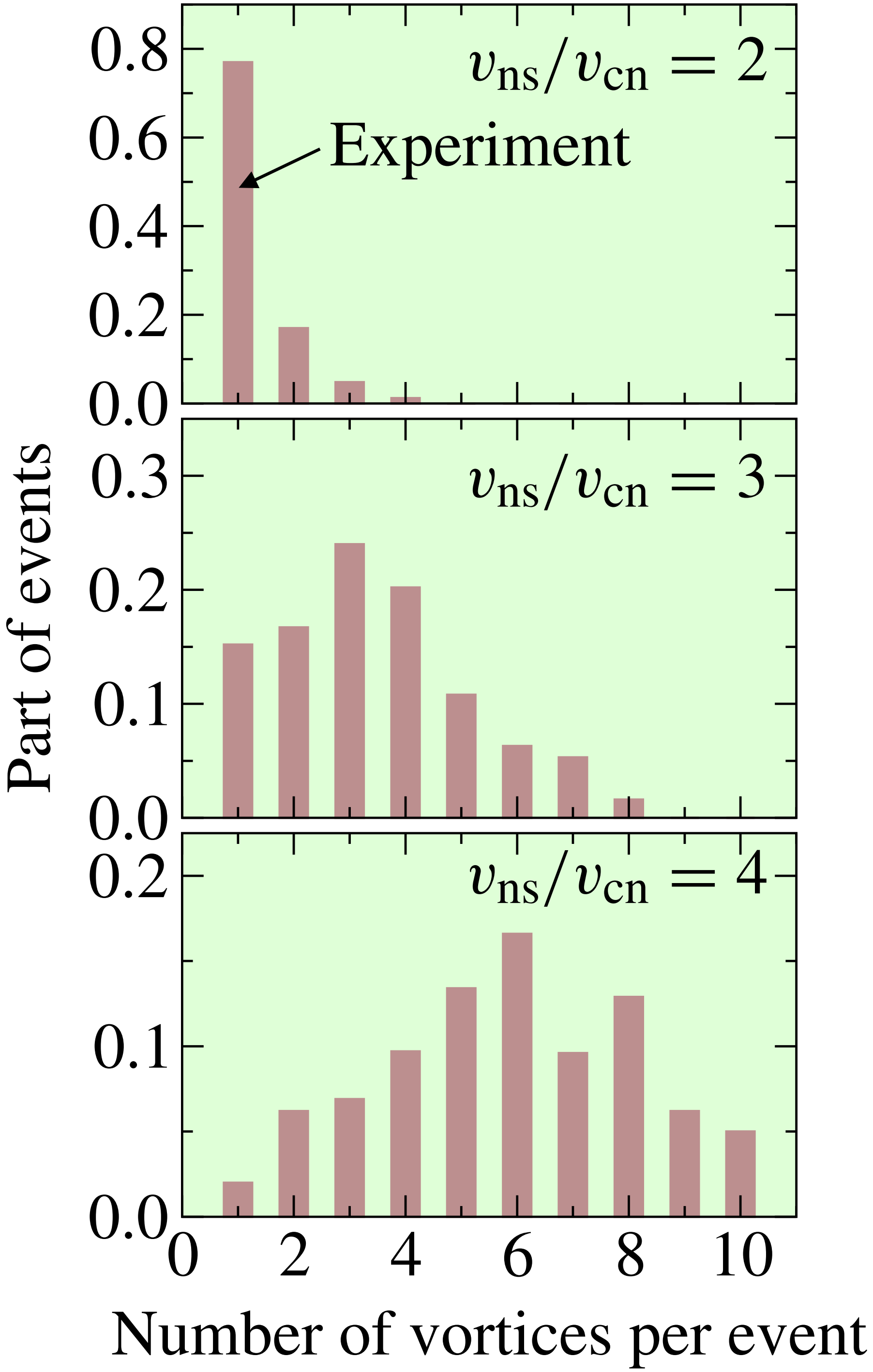
$$R_\mathrm{b} \propto 1/v_\mathrm{cn},\ \ r_\mathrm{c} \propto 1/v_\mathrm{ns} \quad \Rightarrow \quad \dot{N} \propto \phi_\mathrm{n}(v_\mathrm{ns}/v_\mathrm{cn})^3$$



DISTRIBUTION OF EVENT SIZES

Vortex formation is a stochastic process:





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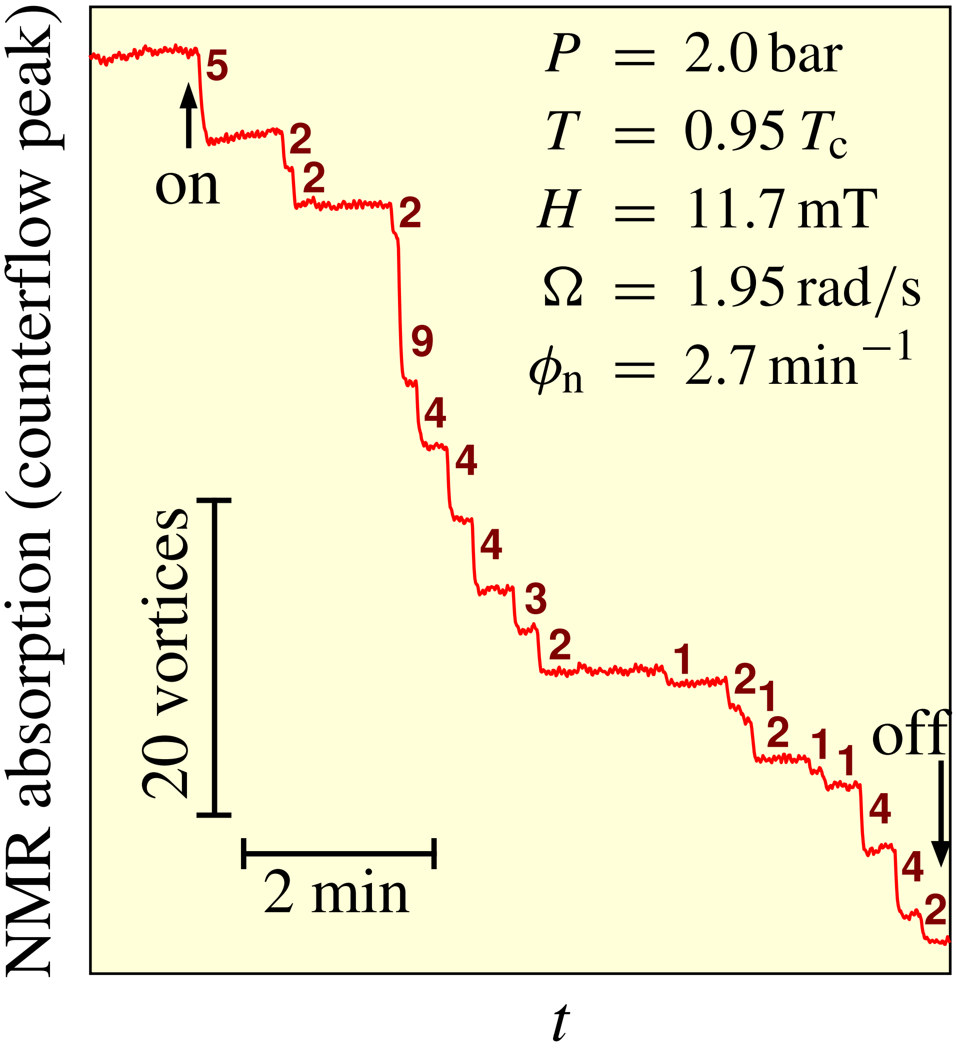
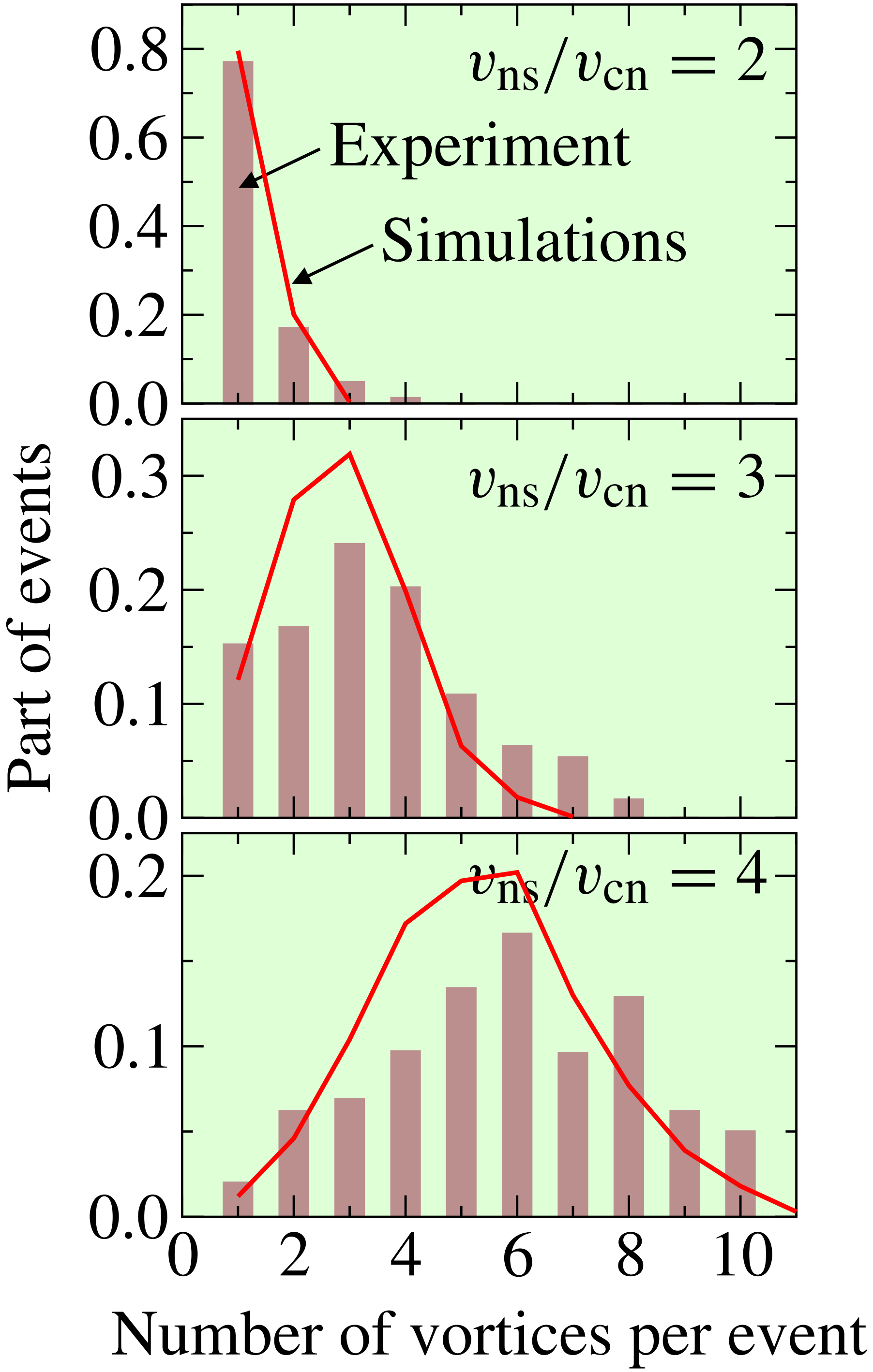
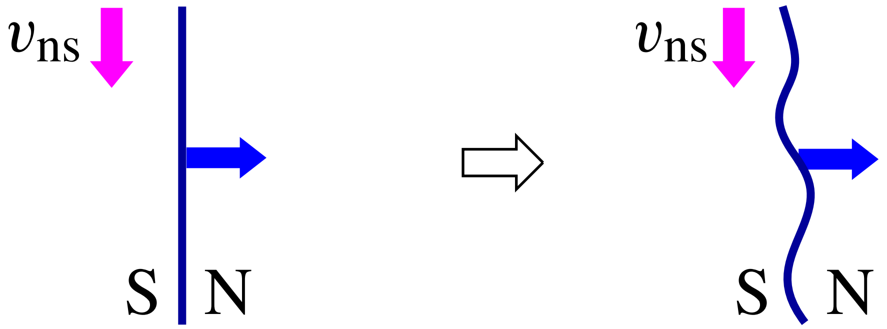


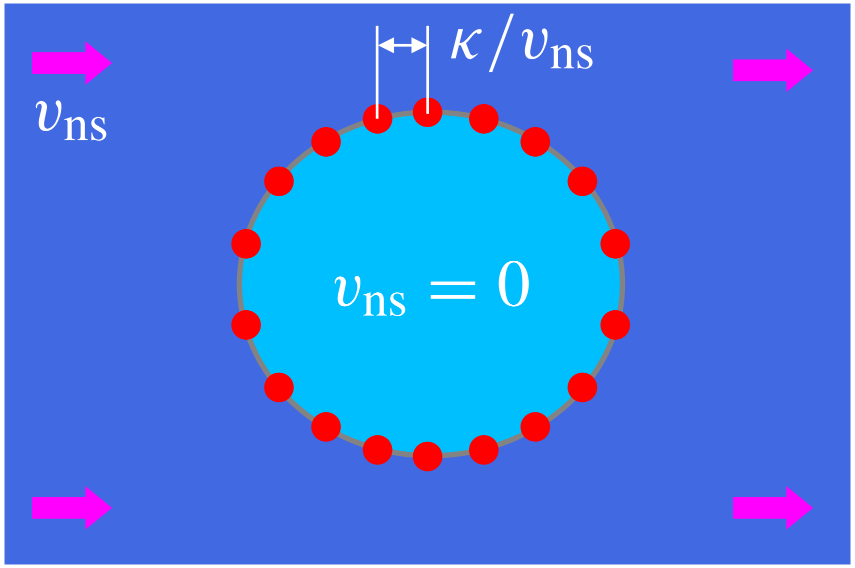


Simulations: Random distribution of vortices in overheated volume.

ALTERNATIVE MECHANISM OF VORTEX FORMATION

Aranson, Kopnin, Vinokur (1999): moving NS interface is unstable in a flow.





Produces vortices in TDGL simulations on the surface of the "bubble".

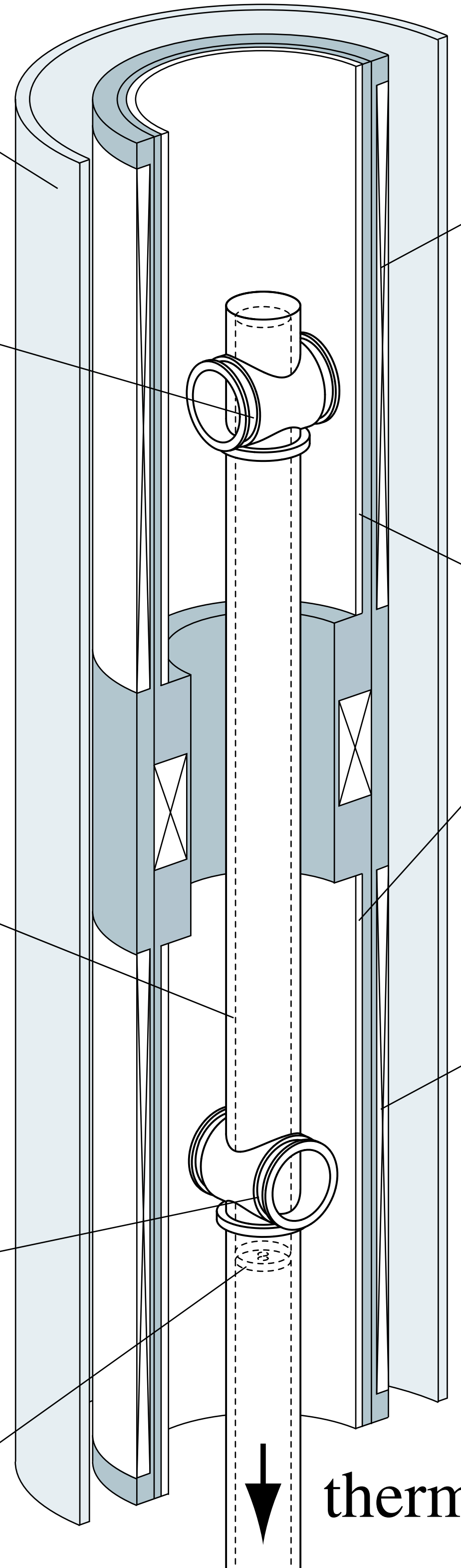
Problems in explaining experimental results:

- Vortex formation rate is linear function of velocity:

$$\dot{N} \sim \phi_{\rm n} \frac{2R_{\rm b}}{\kappa/v_{\rm ns}} \propto \frac{v_{\rm ns}}{v_{\rm cn}}$$

- Vortex number is deterministic.

EXPERIMENTAL SETUP IN RECENT MEASUREMENTS



superconducting Nb shield

magnet for NMR field sweep
top spectrometer

NMR pick-up coil on quartz
coil former (961 kHz)

high-conductivity
rf copper shield

smooth-walled quartz tube
with ^{3}He-B sample
($\varnothing 6 \times 110\,\mathrm{mm}$)

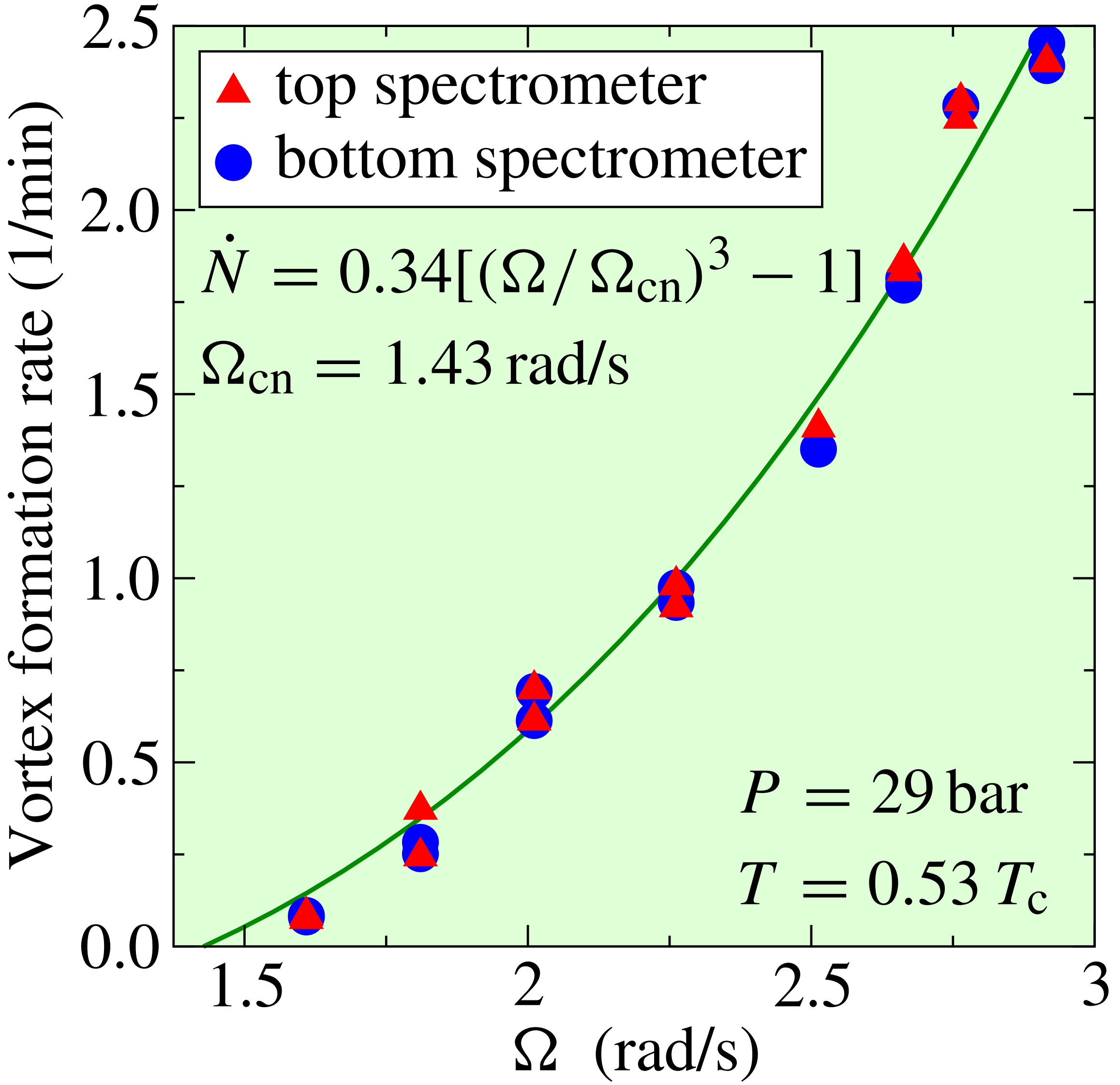
magnet for NMR field sweep
bottom spectrometer

NMR pick-up coil on quartz
coil former (682 kHz)

orifice in partition disc

thermal contact to heat exchanger

VORTEX FORMATION RATE



- $\dot{N} \propto (v_{\rm ns}/v_{\rm cn})^3 - 1$ holds at lower T.
- Neutron flux $\phi_{\rm n} \approx 170\,{\rm min}^{-1}$.

Expected $\dot{N} = \gamma[(v_{\rm ns}/v_{\rm cn})^3 - 1]$ with

$\gamma = 0.07\phi_{\rm n} \approx 12\,{\rm min}^{-1}$.

Got:

29 bar, $0.53\,T_{\rm c}$: $\gamma = 0.34\,{\rm min}^{-1}$,

10 bar, $0.57\,T_{\rm c}$: $\gamma = 2.6\,{\rm min}^{-1}$.

Why universal dependence breaks?

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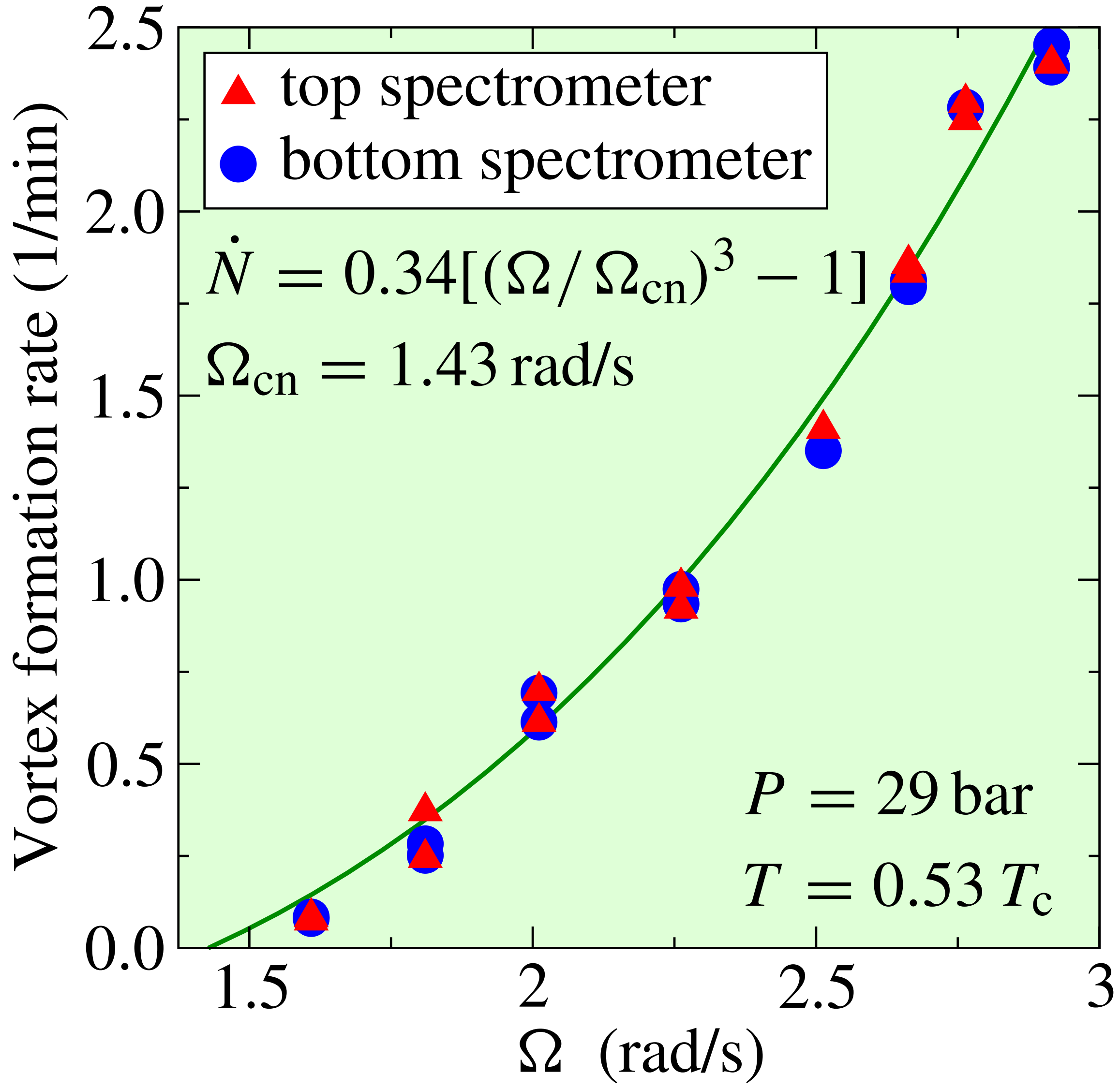

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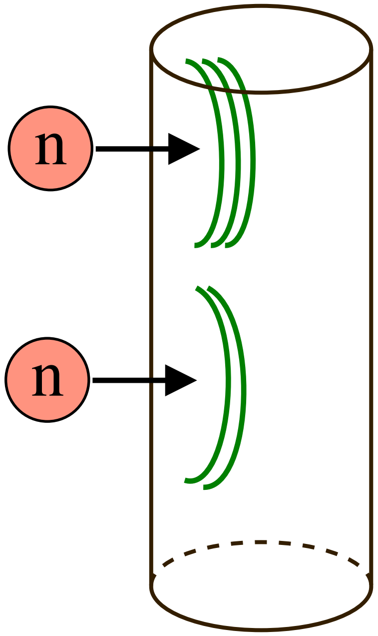
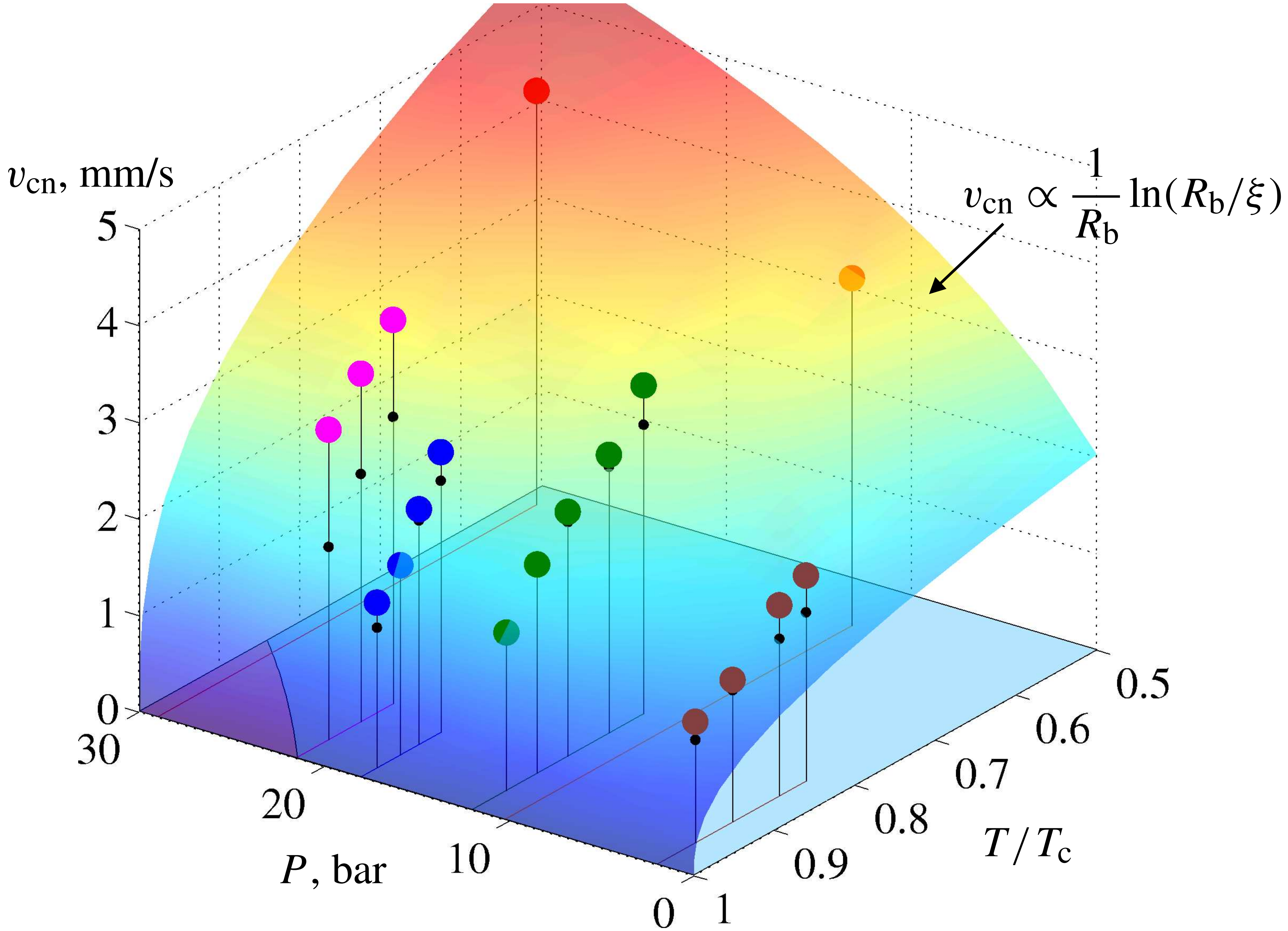


Vortex expansion time along the sample column:

$$\tau = \frac{L}{\alpha \Omega R} \sim 30\,\mathrm{s} \gg 1/\phi_{\mathrm{n}}$$

THRESHOLD VELOCITY



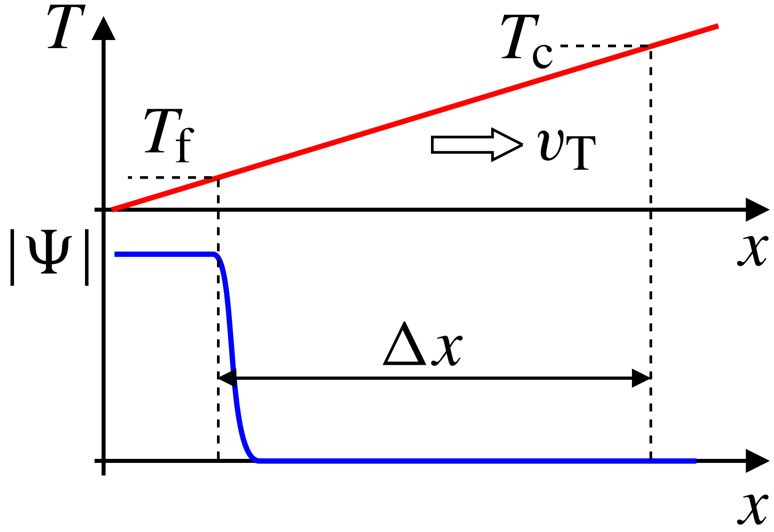
SPECULATIONS ABOUT ROLE OF THE A PHASE

Superfluid transition proceeds as a moving phase front.

(Kibble & Volovik 1997; Kopnin & Thuneberg 1999)

$$\frac{T}{T_\mathrm{c}} = 1 - \frac{t - x/v_\mathrm{T}}{\tau_\mathrm{Q}}$$

$$\Delta x = \frac{v_\mathrm{T}^3 \tau_\mathrm{Q} \tau_0^2}{4\xi_0^2}, \qquad 1 - \frac{T_\mathrm{f}}{T_\mathrm{c}} = \frac{\Delta x}{v_\mathrm{T} \tau_\mathrm{Q}} \sim \left(\frac{v_\mathrm{T}}{v_\mathrm{F}}\right)^2$$



$P = 21.5\,\mathrm{bar}$, $T = 0.9\,T_\mathrm{c}$:

$$T_\mathrm{f} = 0.991\,T_\mathrm{c} \;<\; T_\mathrm{AB} = 0.995\,T_\mathrm{c}$$

$P = 29\,\mathrm{bar}$, $T = 0.5\,T_\mathrm{c}$:

$$T_\mathrm{f} = 0.985\,T_\mathrm{c} \;>\; T_\mathrm{AB} = 0.859\,T_\mathrm{c}$$

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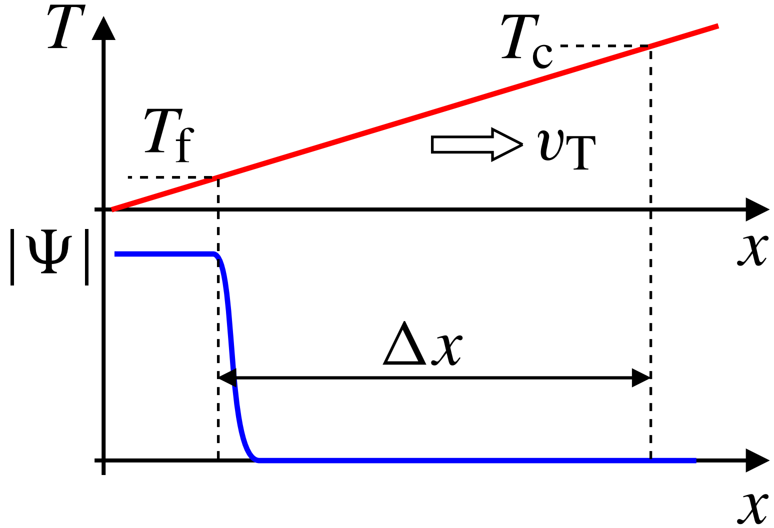

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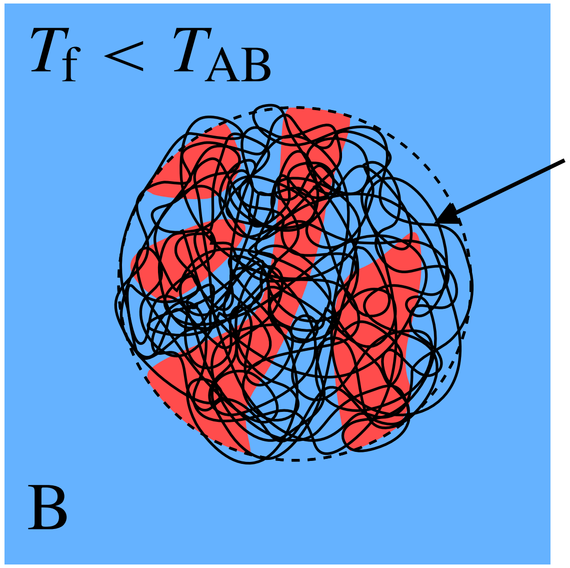
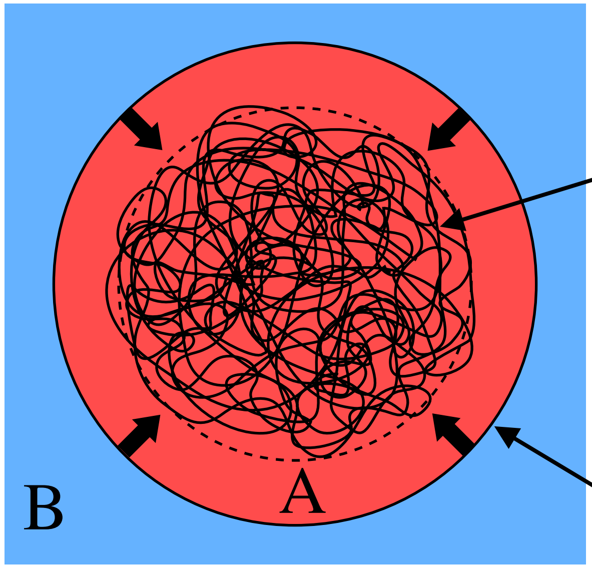


Network of vortices and AB interfaces

(Volovik 1996; Bunkov & Timofeevskaya 1998)

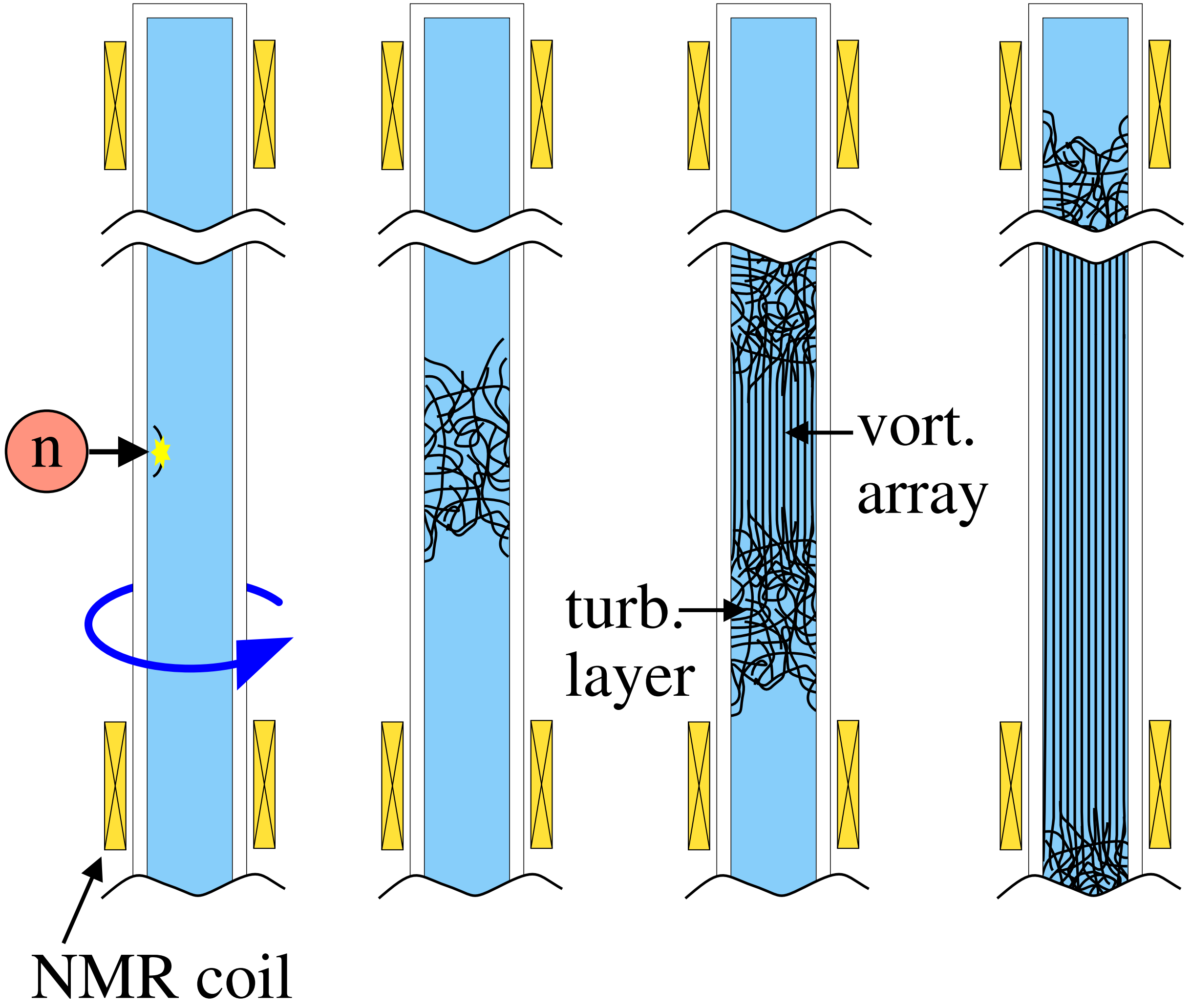


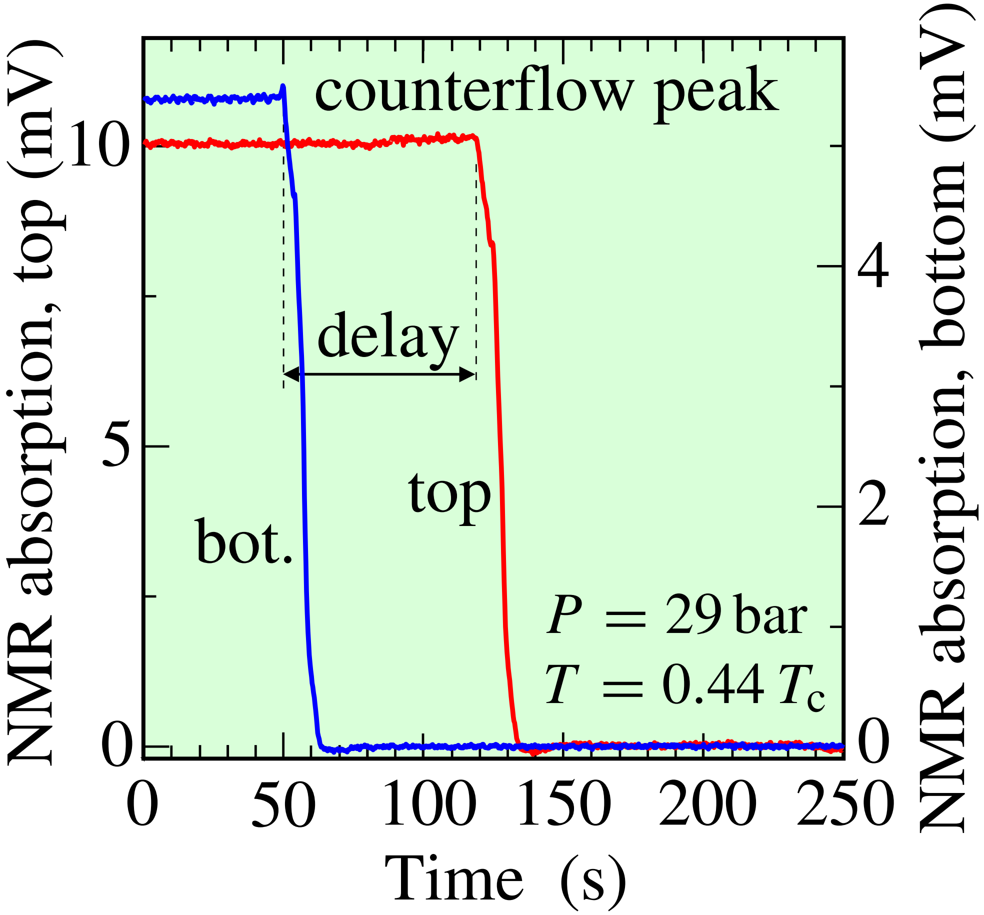
$T_{\mathrm{f}} > T_{\mathrm{AB}}$

Vortices in the A phase

Sweeping AB interface

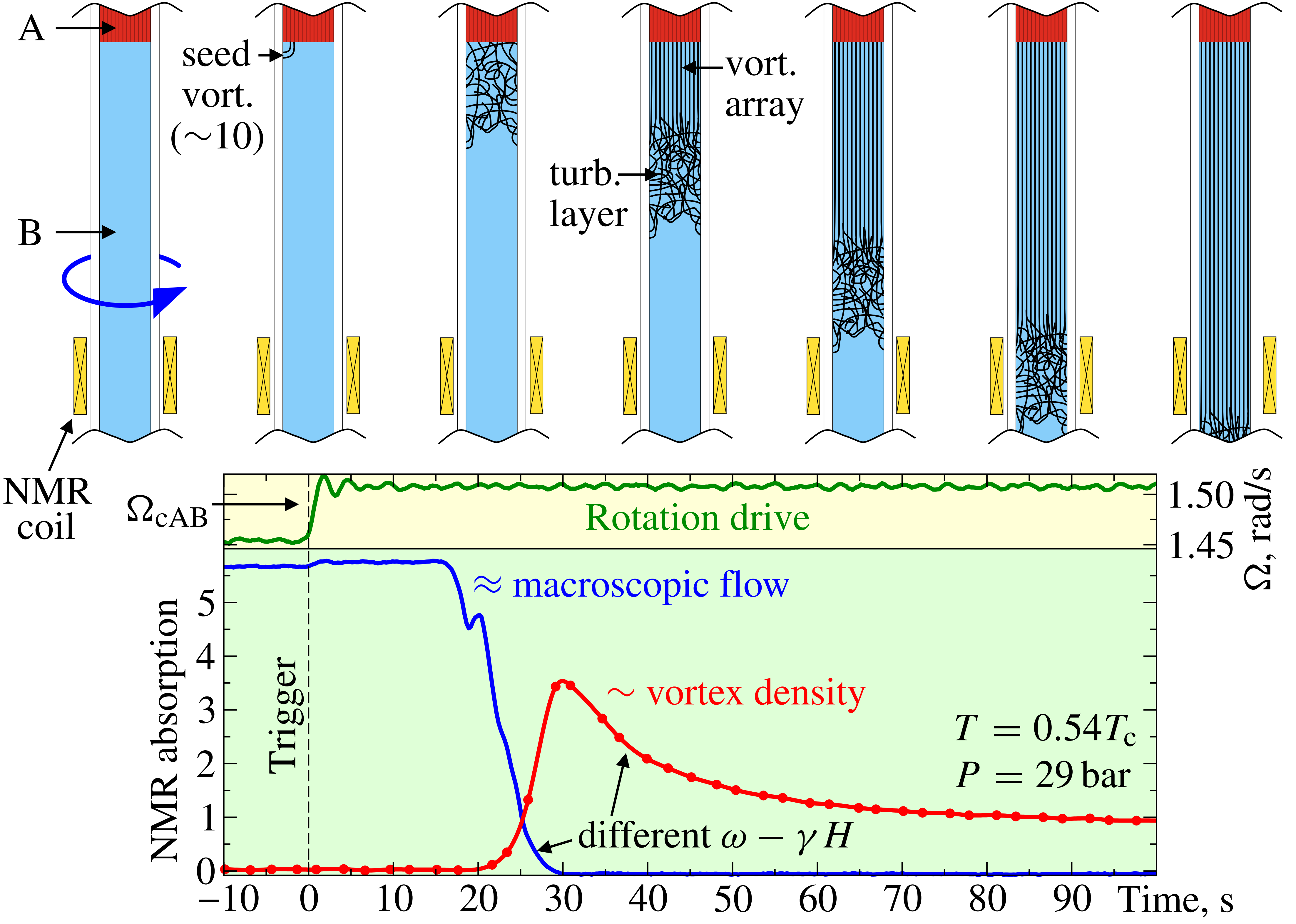
TURBULENCE TRIGGERED BY NEUTRON ABSORPTION



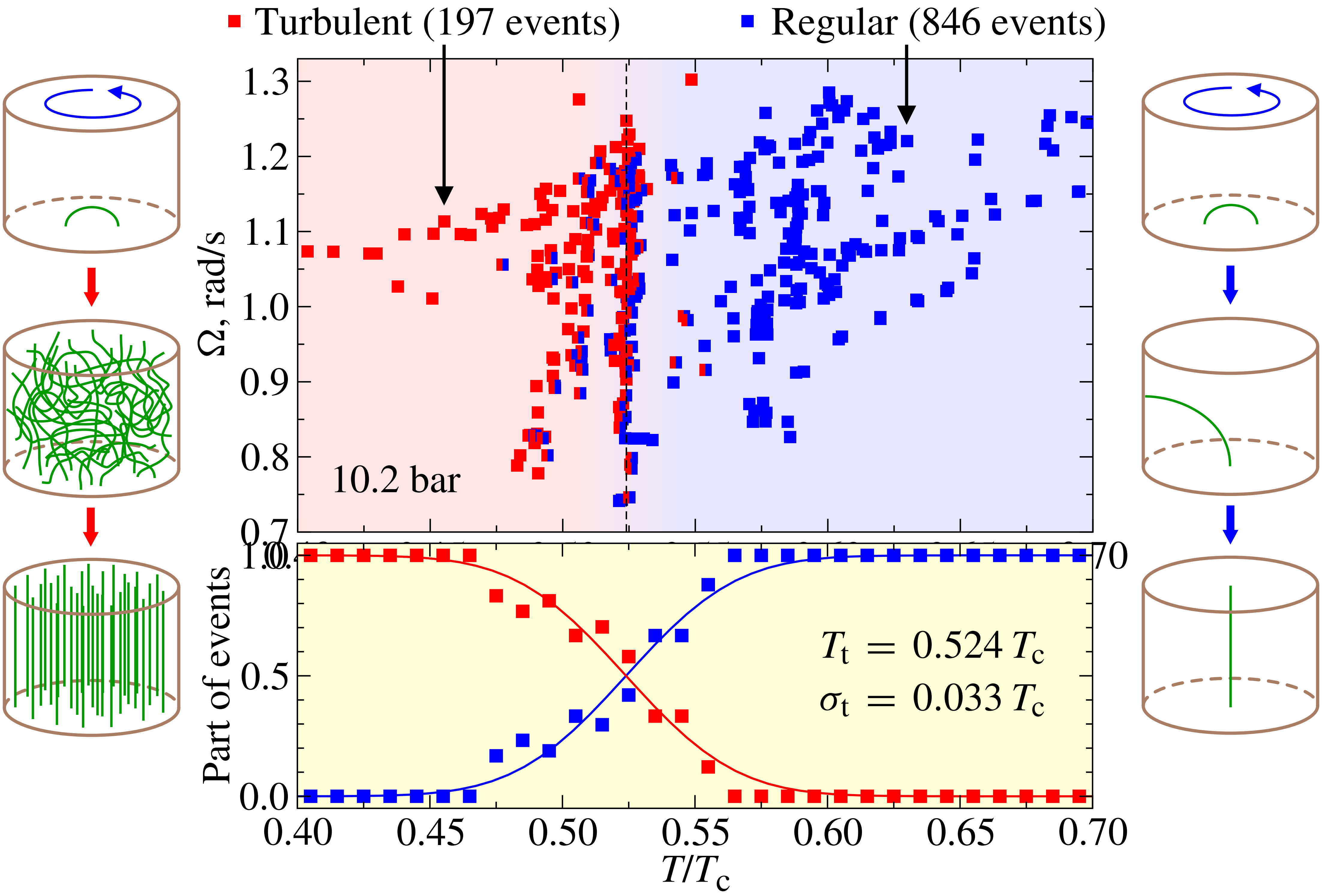


- Vortices injected by neutrons are unstable towards turbulent multiplication at low temperatures.
- Injection position varies but NMR signals are the same ⇒ vorticity expands as a layer in a steady-state configuration.

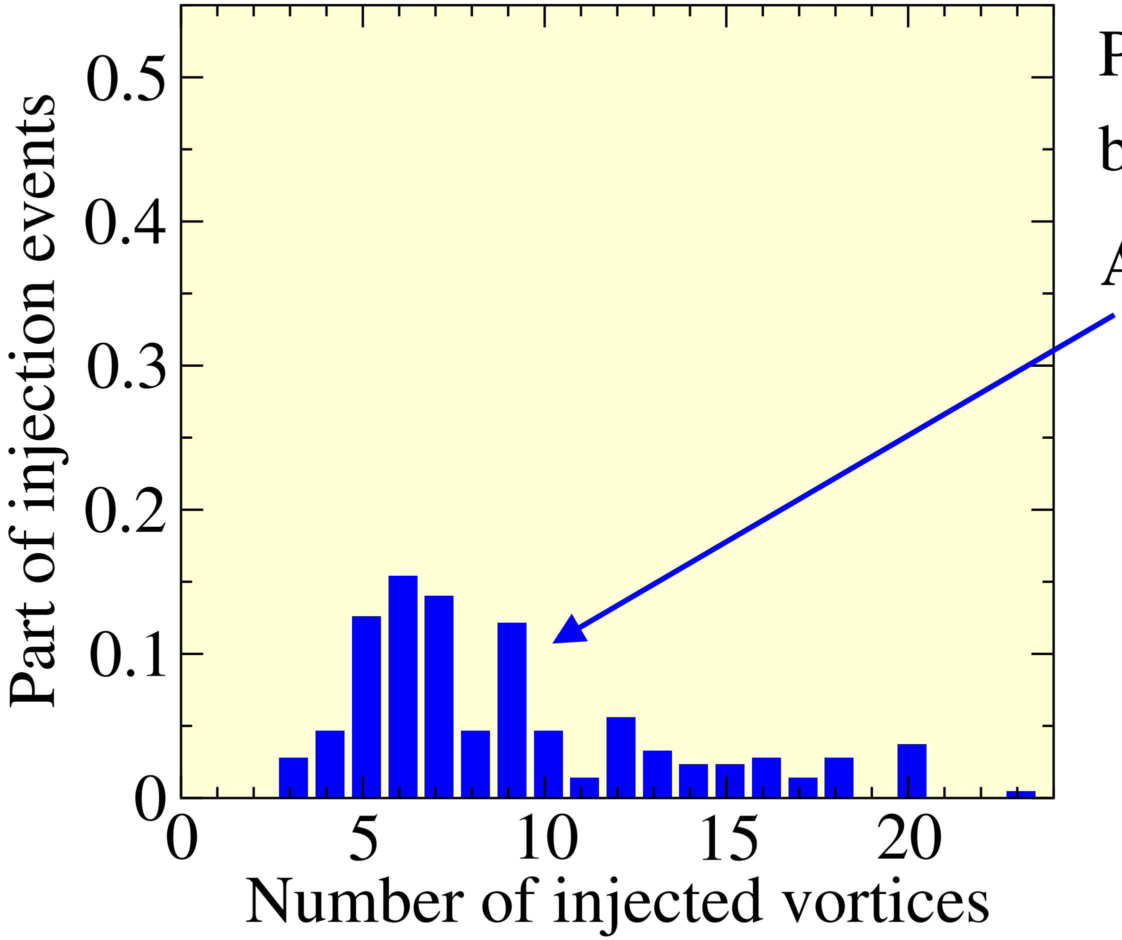
TURBULENCE TRIGGERED WITH AB INTERFACE INSTABILITY



TRANSITION BETWEEN TURBULENT AND REGULAR DYNAMICS (AB INJECTION)



PROBABILITY OF STARTING TURBULENCE AT INJECTION



Probability for a single injection to become turbulent at 29 bar, $0.532T_\mathrm{c}$:

AB injection:

$p_\mathrm{AB} = 0.96 \quad (\Omega = 0.8\text{–}1.6\,\mathrm{rad/s})$

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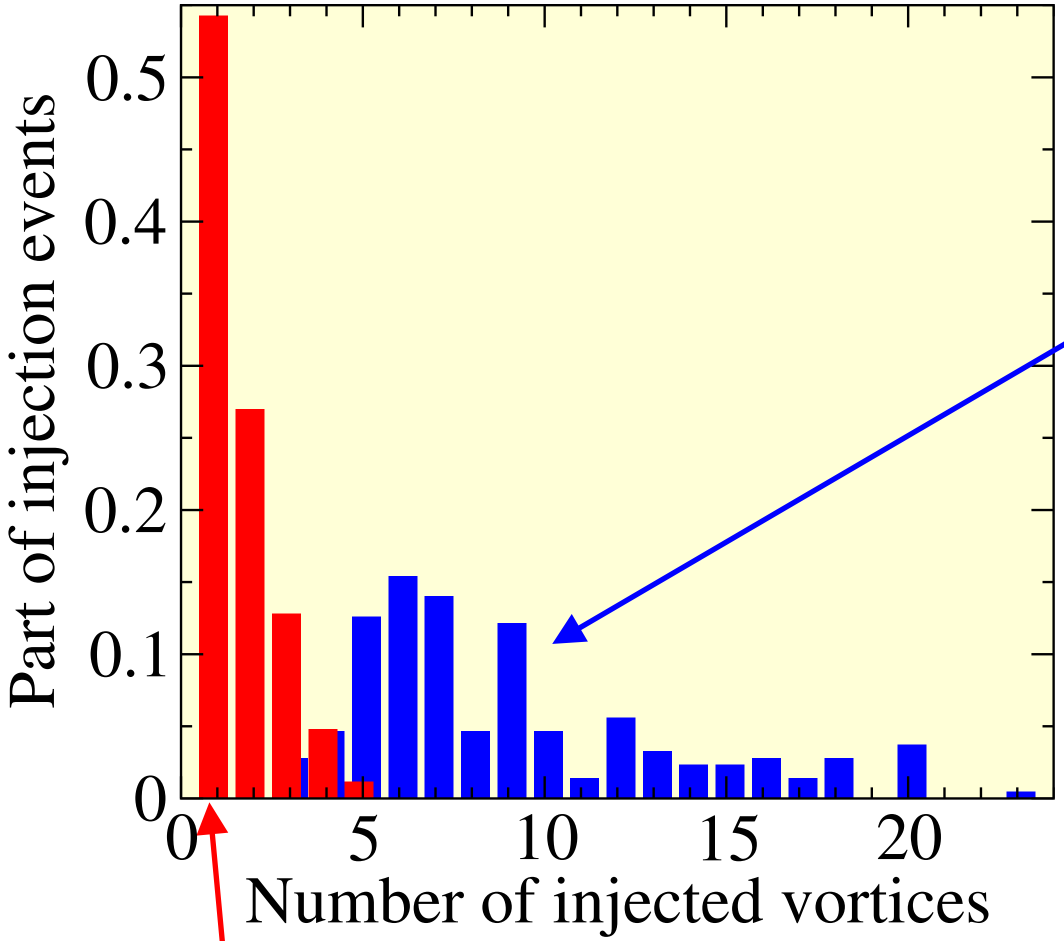

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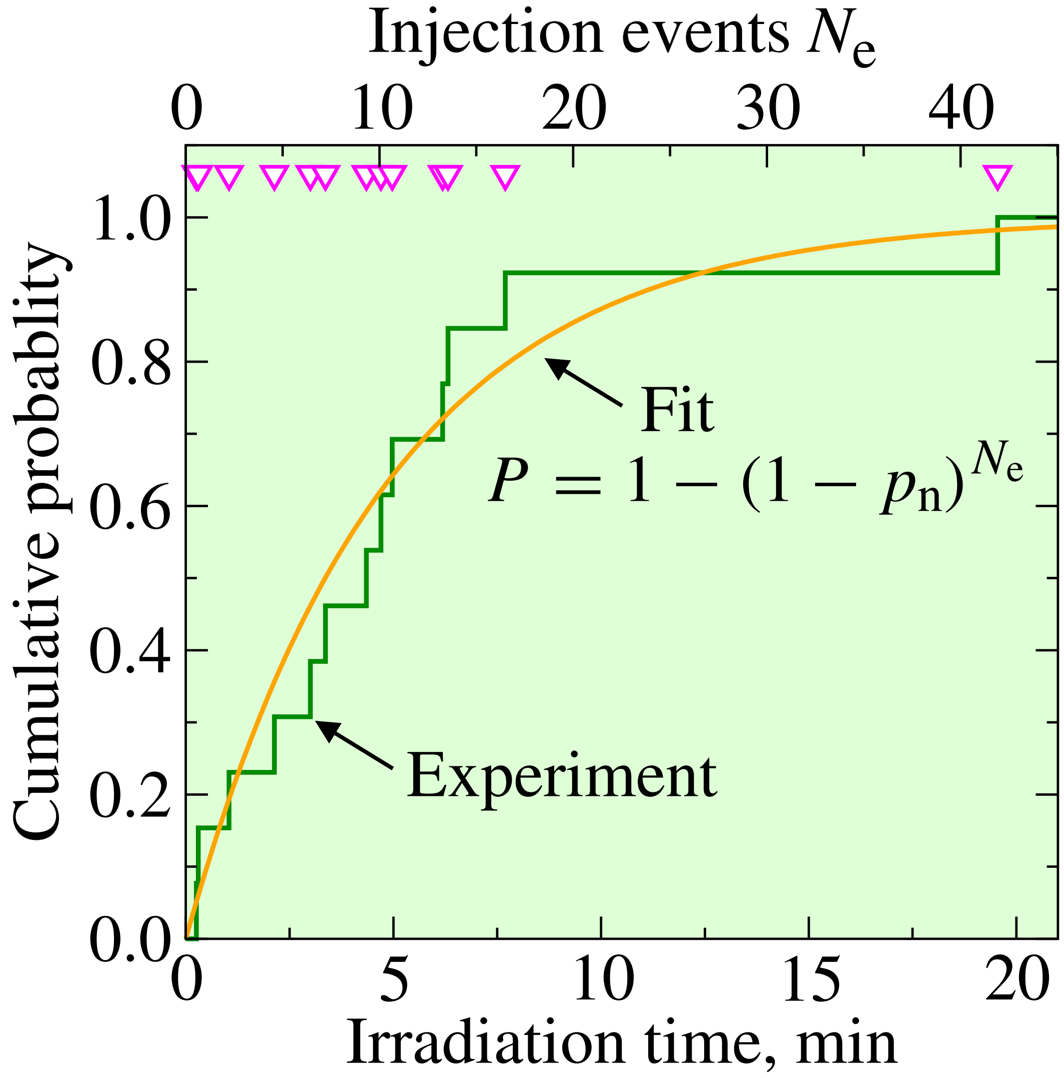
AB injection:

$$p_{AB} = 0.96 \quad (\Omega = 0.8\text{–}1.6\,\mathrm{rad/s})$$

Neutron injection:

$$p_n = 0.092$$

$$(\Omega = 3.32\,\mathrm{rad/s} = 2.32\Omega_{cn})$$



CONCLUSIONS

- Neutron irradiation of vortex-free superflow is a practical means of creating quantized vortices in ^{3}He-B.

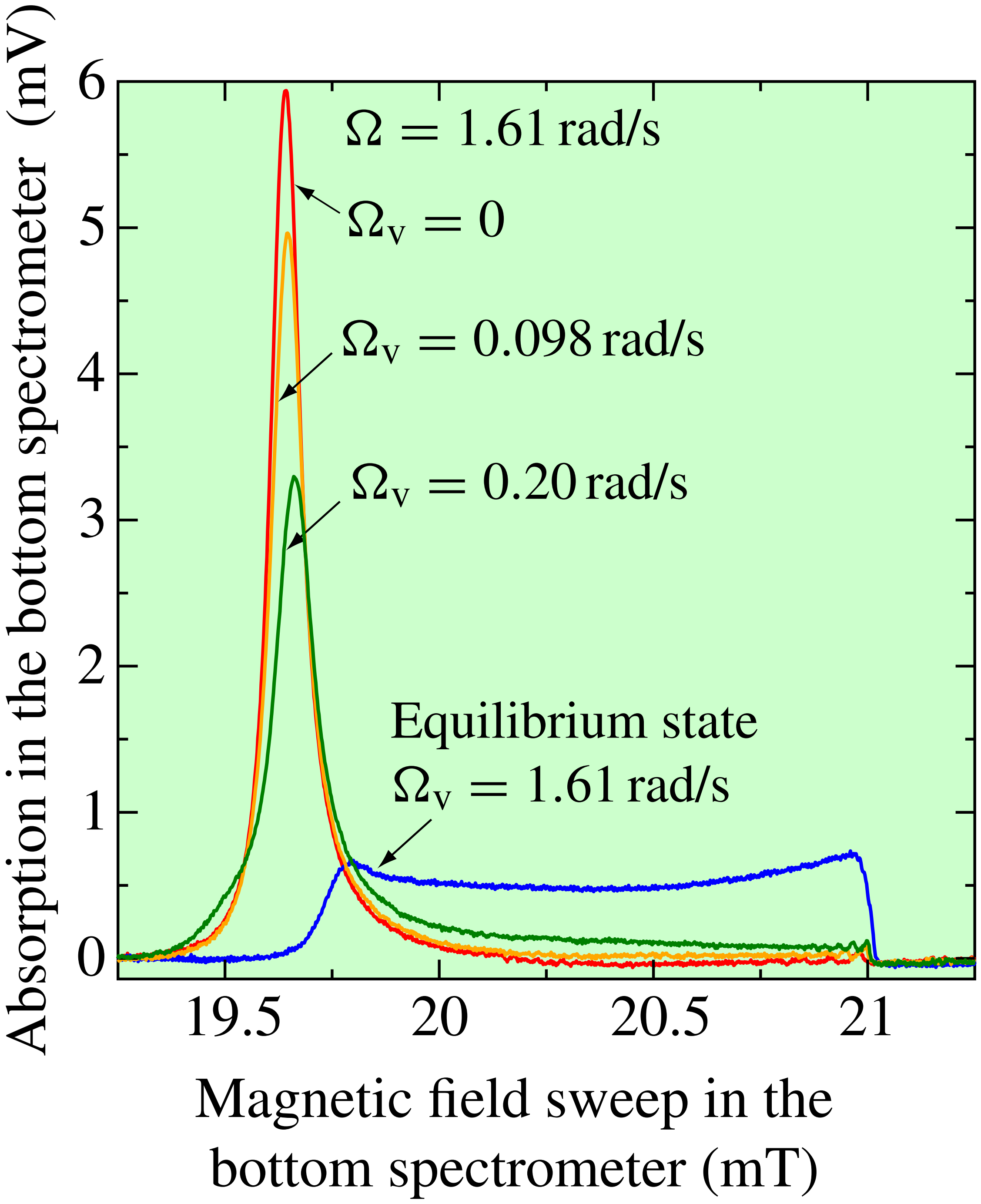
- Experiment shows that vortex loops escaping into the bulk superflow originate from a random vortex network in the interior of the volume overheated by neutron absorption.

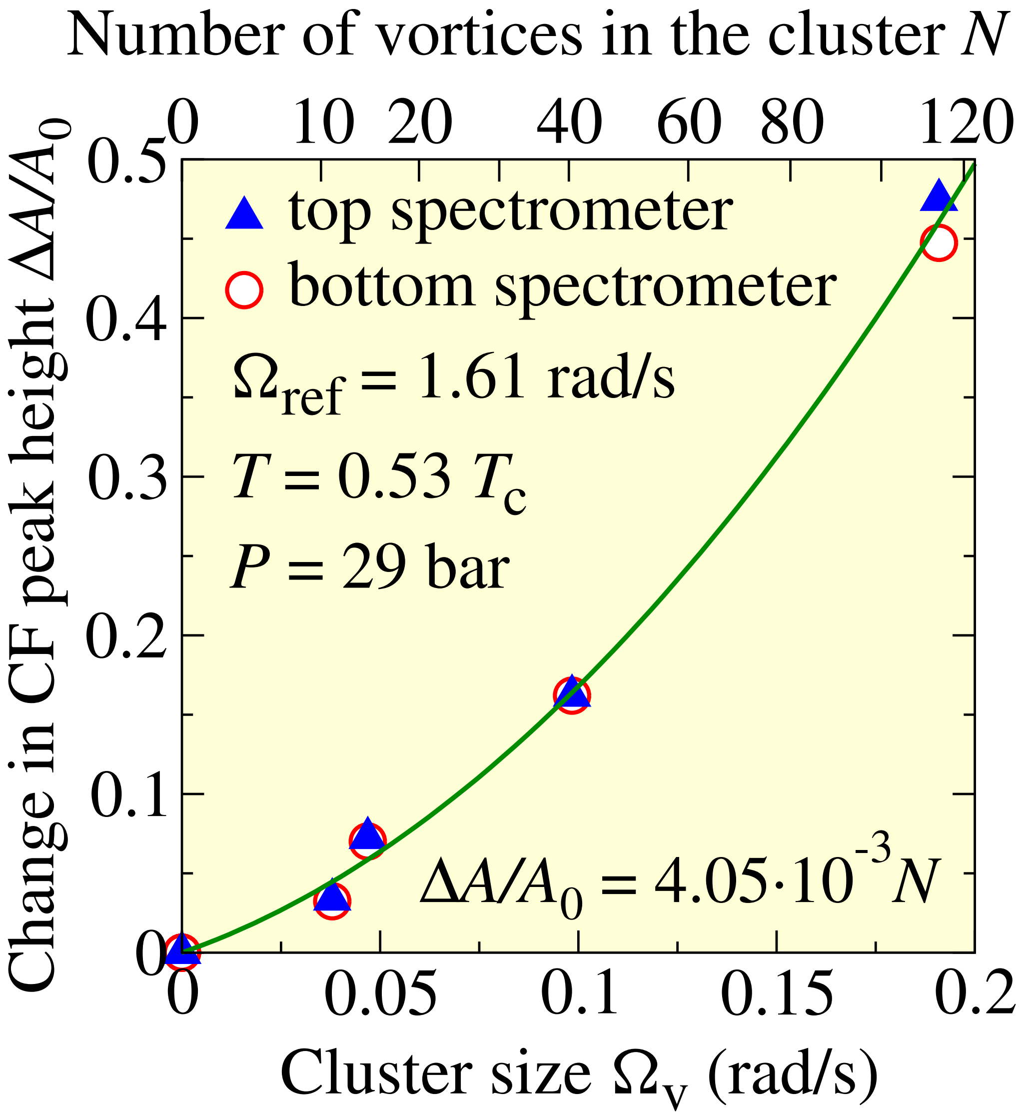
- Cooling through the stable A phase region does affect vortex formation, but no detailed understanding exists.

- Neutron-induced vortex injection is useful for studies of turbulence:
  - Transition between regular and turbulent dynamics.
  - Influence of the initial vortex configuration on the probability to switch on turbulence.
  - Expansion of vorticity as propagating front.

NMR MEASUREMENTS AT LOWER TEMPERATURES

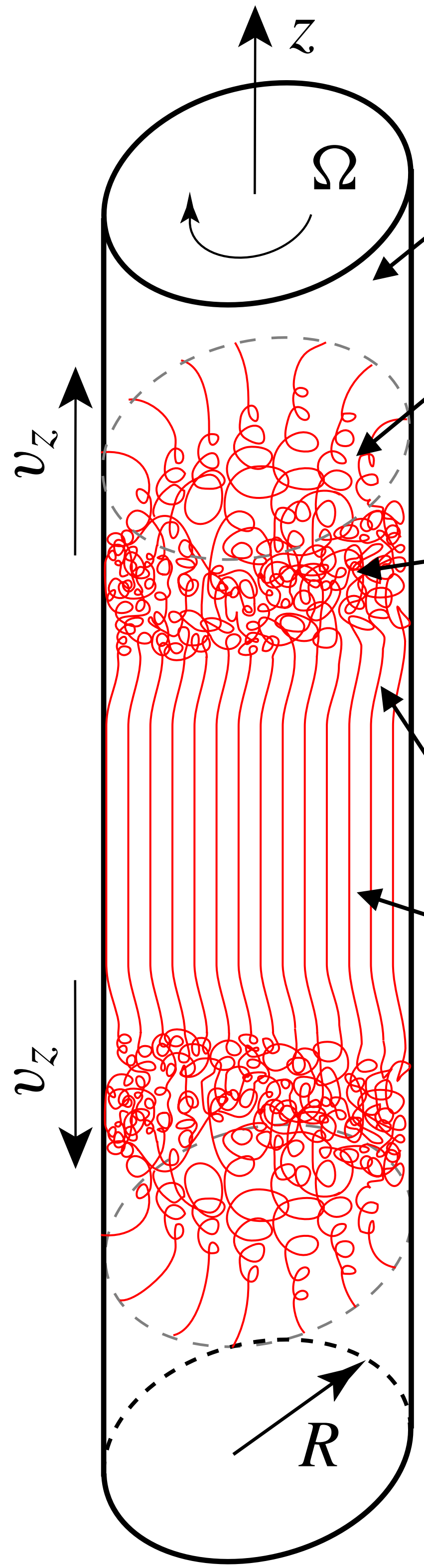
Vortex steps are not visible. Vortex number is determined with calibration:





PROPAGATING TURBULENT LAYER

Axial velocity $v_z \approx \alpha(v_\mathrm{n} - v_\mathrm{s}) = \alpha\Omega R$, like a single vortex.



vortex free
$v_\mathrm{s} = 0$

twisting head
$\langle v_\mathrm{s} \rangle : 0 \to \Omega r$

rear part
$\langle v_\mathrm{s} \rangle \approx v_\mathrm{n}$
turbulence decays

twisting relaxes

equilibrium
vortex array