Does the superclimb of dislocations control the mass accumulation effect in solid ^{4}He ?

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Grand Challenges in QFS, August 7, 2015

Key experiments in hcp ^{4}He

Superflow through the solid and the giant isochoric compressibility (syringe effect):

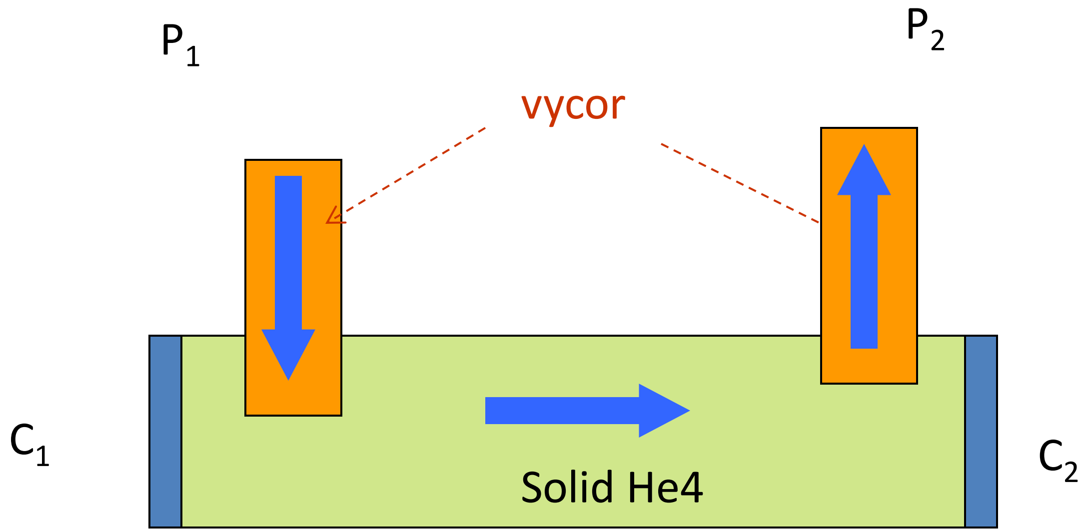
M. W. Ray and R. B. Hallock, PRL 100, 235301 (2008); PRB 79, 224302 (2009); PRB 84, 144512 (2011); Ye. Vekhov and R. B. Hallock PRL. **109**, 045303 (2012); PRL **113**, 035302 (2014) …

Z. G. Cheng, J. Beamish, A. D. Fefferman, F. Souris, S. Balibar,
PRL 114, 165301 (2015);

A. Haziot, Duk Young Kim, M. Chan, March Meeting 2015, A22.00015,

Critical superflow and the syringe effect

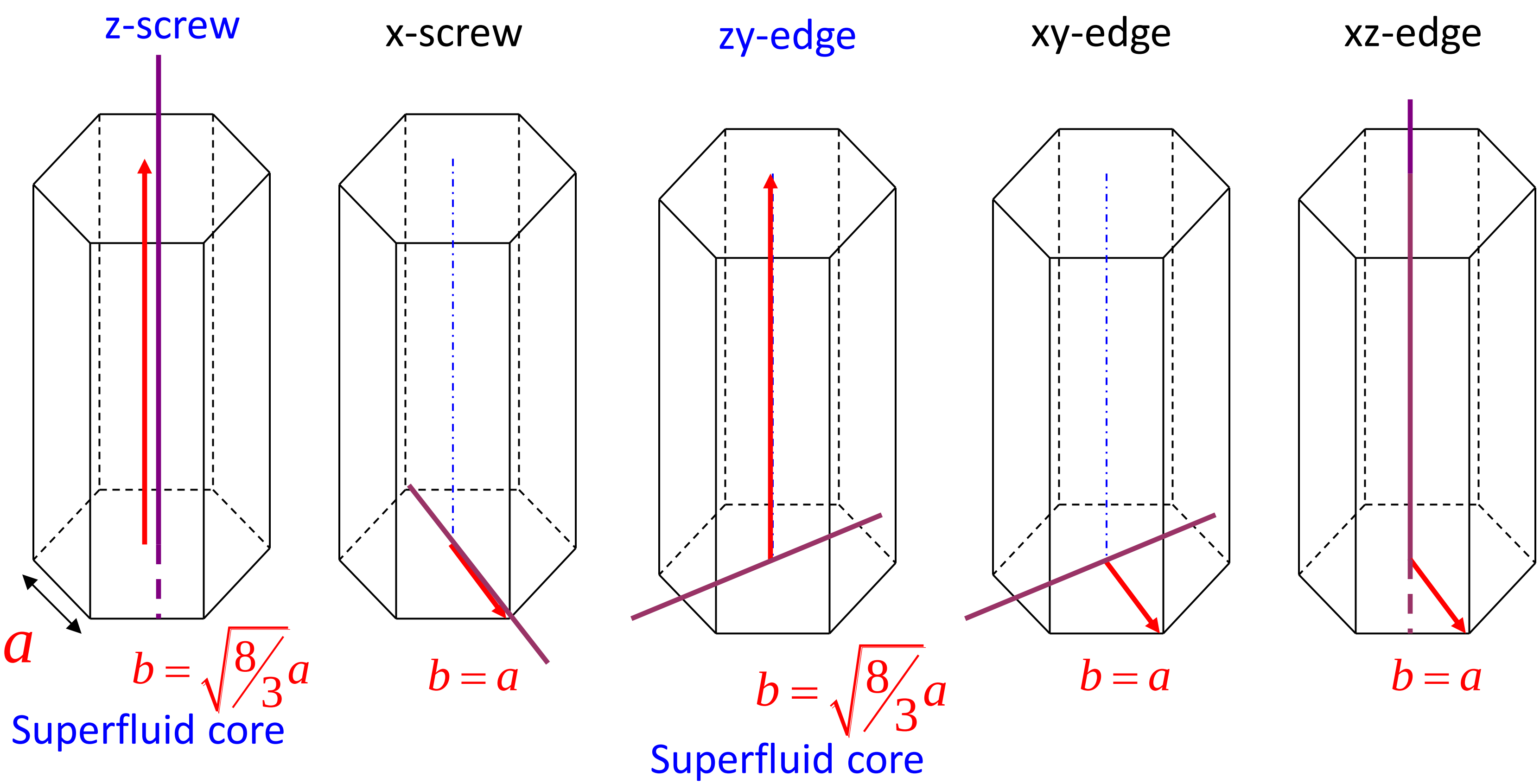
M. W. Ray and R. B. Hallock,PRL **100**, 235301 (2008);PRB **79**, 224302 (2009)



1. Linear in time relaxation of pressure difference – overcritical current ;
2. Flow vanishes above 0.5-0.6K – well below lambda-point
3. Syringe: Large fraction of He4 can accumulate uniformly inside solid during the flow

$$P(C_1) – P(C_2) = \text{const}(t)$$

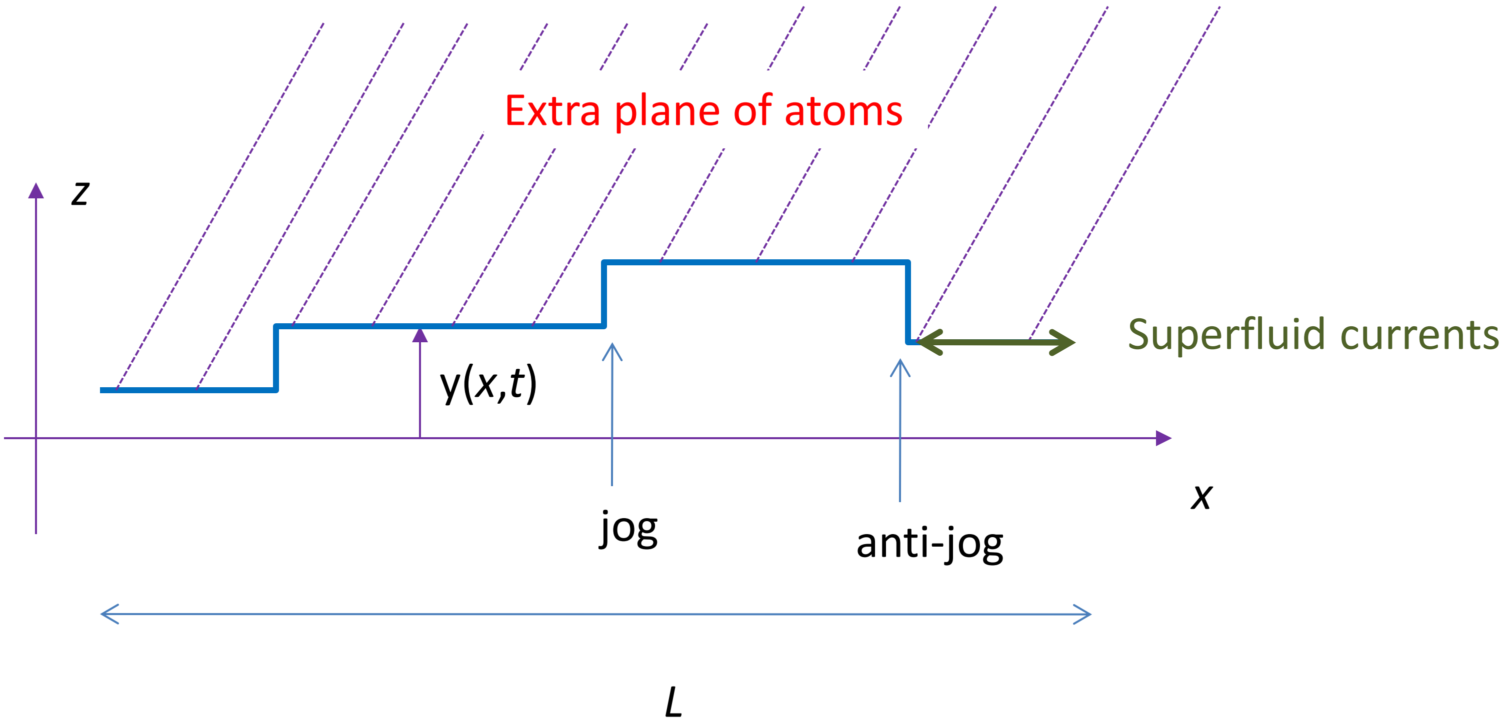
Dislocations in hcp ^4He



Ab initio MC:
M. Boninsegni, ABK, L. Pollet,
N.V. Prokof'ev, B.V. Svistunov,
M. Troyer, PRL **99,** 035301 (2007)

Ab initio MC:
S. G. Soyler, ABK, L . Pollet, N.V. Prokof'ev, B.V. Svistunov,
PRL 103, 175301 (2009)

Syringe effect due to edge superclimbing dislocation carrying quantum liquid of geometrical jogs

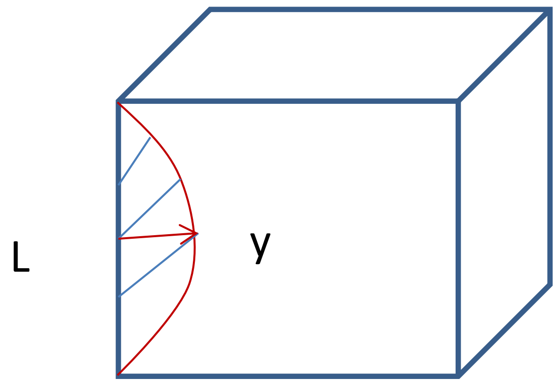


The excitation spectrum is ~ q^2 so that it is a non-Luttinger liquid

S. G. Soyler, ABK, L . Pollet, N.V. Prokof'ev, B.V. Svistunov,PRL 103, 175301 (2009)

"Giant" isochoric compressibility: Linear response

The edge planes can accumulate extra atoms like a liquid regardless of the dislocation density



$$\delta N \sim yL, \qquad |y| << L$$

$$y \sim \delta\mu L^2,$$

$$\delta N / \delta\mu \sim L^3 \sim N$$

μ - bias by chemical potential

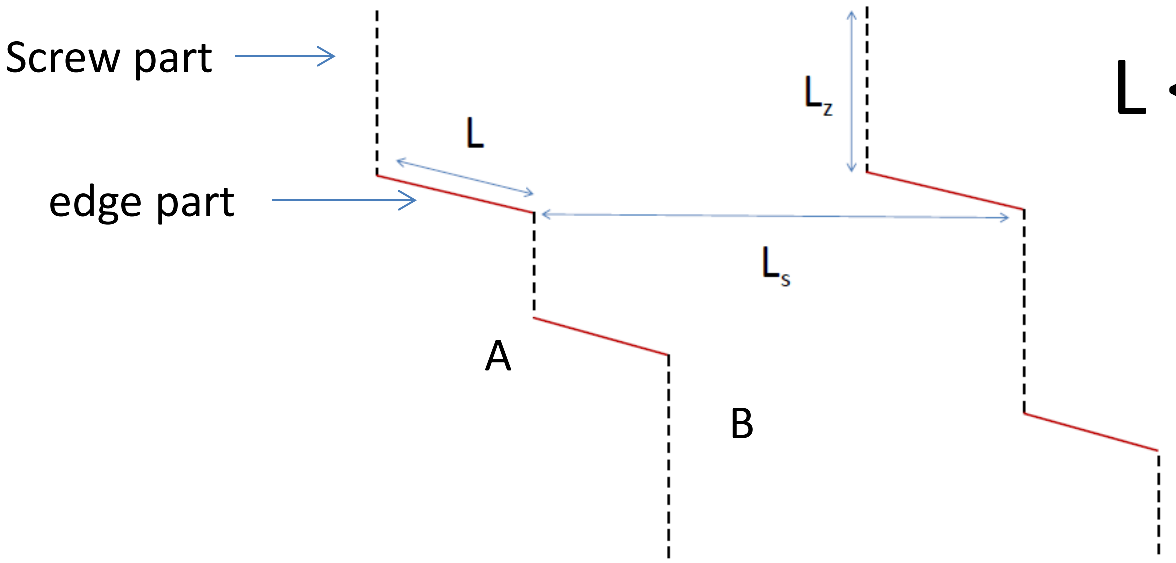
$$\frac{dN}{d\mu} \sim N$$: Liquid-like response

Maximum linear compressibility is achieved when a typical length of the superclimbing segments is comparable to a distance between the segments

$$\frac{d\ln N}{d\mu} \sim \frac{1}{(K+G)b^3}$$

K – compression modulus
G-shear modulus

Asymmetrically small density of superclimbing segments



$L << L_S$ and $L << L_z$

Syringe fraction: $$\frac{\Delta N}{N} \approx \frac{L^3}{L_s^2 L_z} \frac{\mu}{G b^3} << \frac{\mu}{G b^3}$$

The syringe fraction in the linear regime (small bowing) does NOT depend on dislocation density --- only on its geometry --- the ratio of the lengths, provided the network is uniform

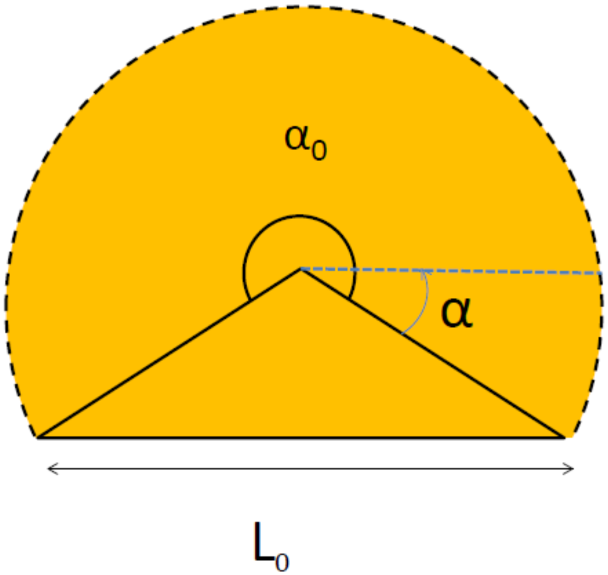
Syringe bistability of solid ^{4}He

Three channels:

1. Injection of edge dislocations with SF core from vycor;
2. Bardeen-Herring loop generation from the edge segments;
3. Helical instability of screw dislocations with SF core

All are characterized by essentially the same threshold in chemical potential μ bias: μ_c ~ 1/dislocation length

Edge dislocation with superfluid core becomes unstable toward unlimited inflation under the bias by chemical potential with the threshold ~ 1/dislocation length



$$E = \frac{Gb^2}{4\pi} R \cdot \alpha_0 - \frac{|\mu|}{b^2} R^2 \cdot (\alpha_0 - \sin\alpha_0)$$

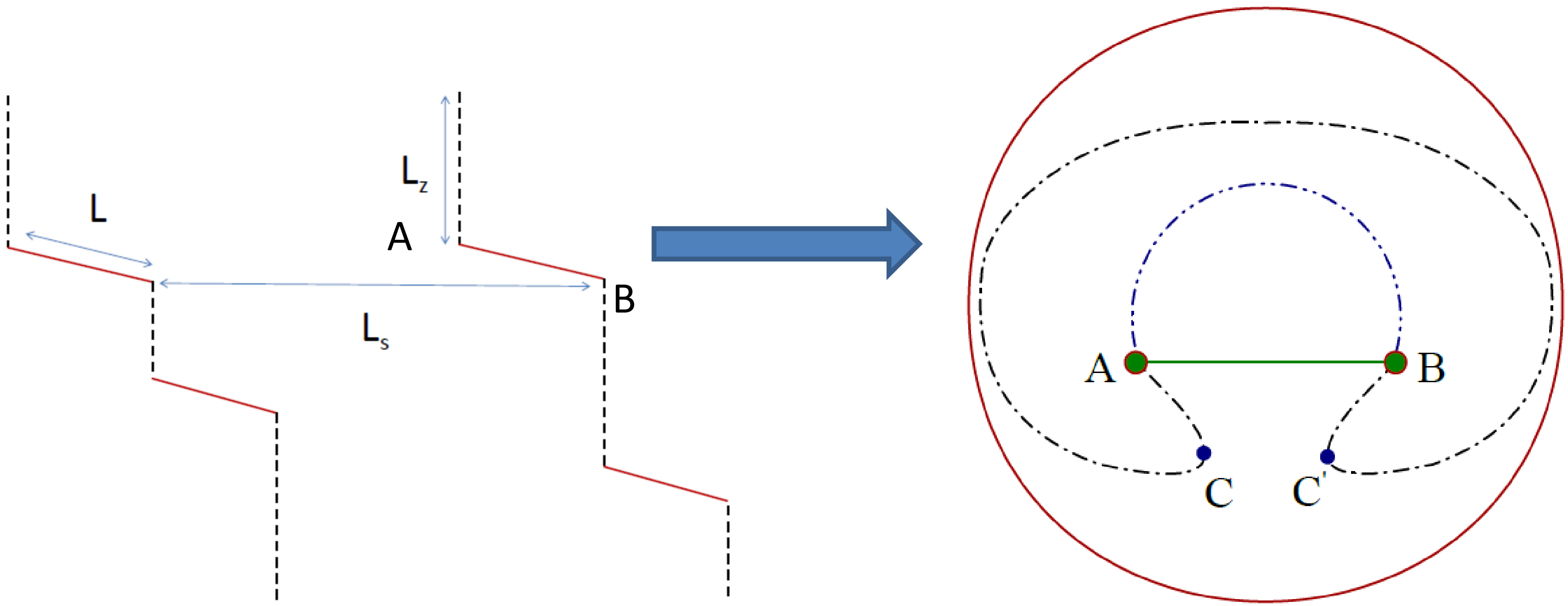
Dislocation core energy

Work by bias to add extra matter – orange area under the curve

Absolute instability toward unlimited inflation for

$$|\mu| > \mu_c = \frac{Gb^4}{2\pi L_0}$$

Bardeen-Herring loop generation supported by the core superflow

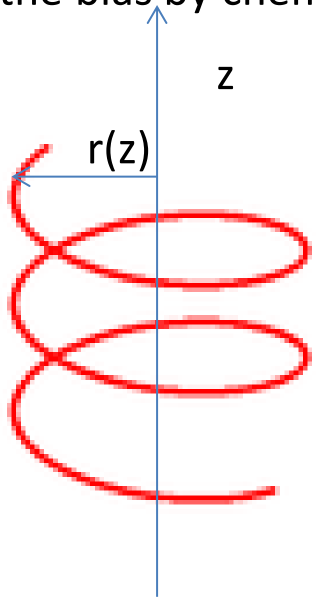


Asymmetrically small density of superclimbing segments

$$L \ll L_S \text{ and } L \ll L_z$$

Syringe instability of screw dislocation

Screw dislocation with superfluid core develops helix with the additional matter accumulation under the bias by chemical potential with the threshold ~ 1/dislocation length



$$E_s = \int_0^L dz \left\{ \frac{\mu \gamma_s r^2}{2} \partial_z \theta + \frac{\epsilon_c}{2} [(\partial_z r)^2 + r^2 (\partial_z \theta)^2] \right\}$$

Work by bias to add extra matter “inside” the helix

Dislocation core energy

$$\partial_z \theta = -\frac{\mu \gamma_s}{2\epsilon_c}, \quad \Rightarrow \quad E = \int_0^L dz \left\{ -\frac{(\mu r)^2}{8\epsilon_c} + \frac{\epsilon_c}{2} (\partial_z r)^2 \right\}$$

Absolute instability

$$|\mu| > \mu_c \approx \frac{G b^4}{2\pi L_0}$$

Realistic values

G~ 200 bar, b ~ 3.5A, L_0~ 10^{-2}- 10^{-3}cm

⇩

μ_c~5· (10^{-5}-10^{-4}) K or DP_c ~ 0.2-2 mbar

UMASS : μ ~ 0.001-0.01 J/g = 5·10^{-4}-5·10^{-3}K

Univ. of Alberta: DP ~ 2-8 mbar

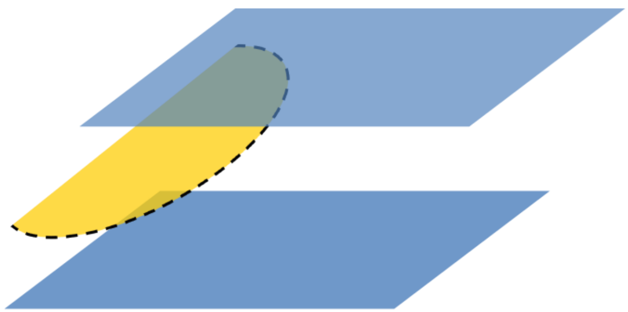
Actual free length L_0 should be much bigger than the inter-dislocation distance because crosspining does not work well for superclimb --- it costs no energy to create a jog

The experiments are likely to be in the overcritical regime!

At small dislocation densities ~ $1/L^2$ the bias needs to be ~ L^2 to see the flow. So, it is easy to be way above the threshold which is ~ 1/L

Ballistic growth of the superclimbing loop from the vycor-solid boundary

ABK, arXiv:1507.06966



$$\frac{dR^2}{dt} \approx \rho_s \frac{\phi_0}{R}, \quad \frac{d\phi_0}{dt} = \mu$$

Syringe fraction: $$\frac{\Delta N}{N} \propto (\rho_s|\mu|)^{1/3} t^{2/3}$$

Flow velocity along the rim: $$V_0 = \frac{\hbar}{mb}\left(\frac{t}{\tau_b}\right)^{1/3}$$

$$\tau_b^{-1} = \frac{3\pi\mu^2 b}{4\rho_s} \approx 2.4 \frac{\mu^2 mb}{\hbar^3 n_s^{(1d)}}$$

Superfluid density along dislocation core:

ρ_S, $n_s = m\,\rho_S \sim 1\ A^{-1}$

About 1ms to reach speed ~ 100m/s for $\mu \sim 10^{-4}$K

Dissipative regime

$$\frac{dV_0}{dt} + \gamma V_0 \approx \frac{\mu}{mR}, \qquad \frac{\pi dR^2}{dt} = 2\rho_s V_0$$

Phase slip rate:

C. Kane & M. Fisher

N. Prokof'ev & B. Svistunov

$$\tau_{ps}^{-1} \sim \gamma V_0 = \gamma_0 \mathrm{Im}[bT + iV_0]^{1/p}$$

The flow rate ~ μ^p as observed in "UMASS sandwich"

Syringe fraction

Dissipative non-linear:

$$\frac{\Delta N}{N} \propto R \propto \left(\frac{|\mu|}{\gamma_0}\right)^{\frac{p}{2+p}} (\rho_s t)^{\frac{1}{2+p}}$$

Dissipative linear (Ohmic):

$$\frac{\Delta N}{N} \propto R \propto T^{\frac{1-p^{-1}}{3}} \left(\frac{\rho_s |\mu| t}{\gamma_0}\right)^{\frac{1}{3}}$$

Rate of the Bardeen-Herring loop generation

Ballistic:

$$\frac{d\Delta N}{dt} \propto \frac{(\rho_s|\mu|)^{1/2}}{L_0^{3/2}}$$

Dissipative non-linear:

$$\frac{d\Delta N}{dt} \propto \frac{\rho_s|\mu|^p}{\gamma_0^p L_0^{2+p}}$$

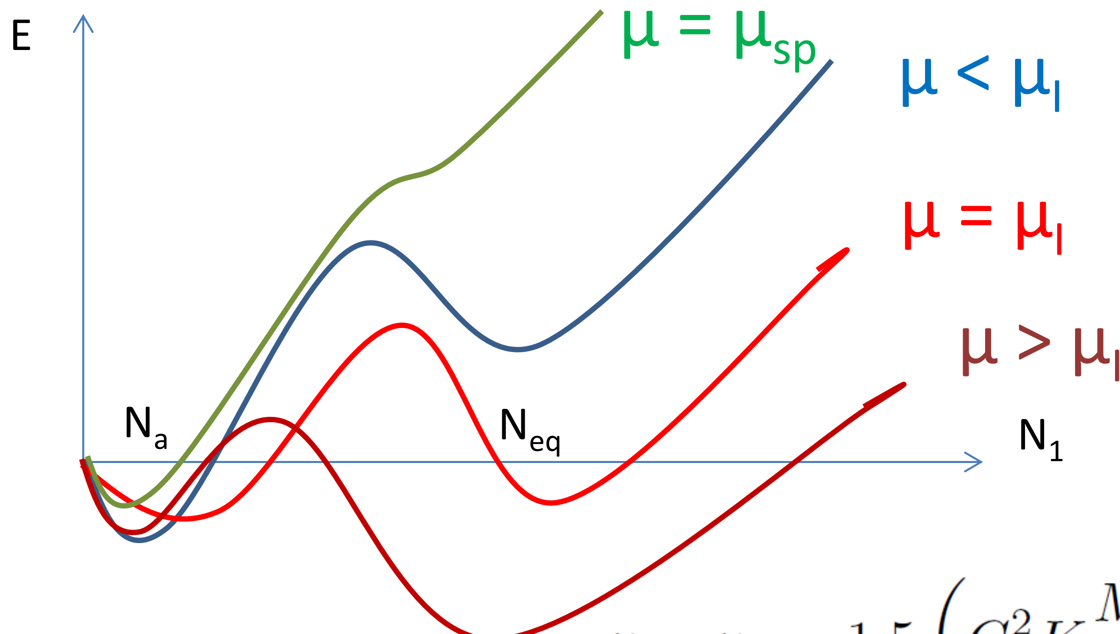
Dissipative linear (Ohmic):

$$\frac{d\Delta N}{dt} \propto \frac{\rho_s T^{(1-p^{-1})}\,|\mu|}{\gamma_0 L_0^3}$$

Hysteresis

In an almost perfect solid ^{4}He with low density of superclimbing segments there are two solutions for the syringe fraction:

1. N_a -- due to small bowings of superclimbing segments at small μ (below the threshold)
2. N_{eq} – max syringe fraction ~ μ/(K+G)



First order "phase transition" at

$$\mu = \mu_I = 1.5 \left(G^2 K \frac{M}{\Omega} \right)^{1/3} b^4.$$

Hysteresis vanishes at

$$\mu_{sp} = 2^{-1/3} \mu_I \approx 0.794 \mu_I$$

Main implication

Growth and proliferation of superclimbing dislocations under the bias, so that the "conducting" network can be created even if it didn't exist originally.

Challenges in solid ^{4}He

- Detailed experimental data on the time and the bias dependencies of the syringe fraction are needed to compare with the theoretical predictions
- The origin of the temperature dependence ~ 1- exp(-Ea/T) (UMASS)
- How is the index p (UMASS) related to the Luttinger parameter? [Mechanisms of the phase slips]
- Phase slips in the non-Luttinger liquid – superclimbing dislocation
- Dependence of the flow rate and the syringe on controlled structural disorder – creation of screw dislocations by twisting; shearing etc.