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超流動自由表面直下の二次元イオン系を用いた超流動臨界速度の観測

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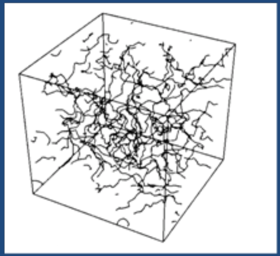
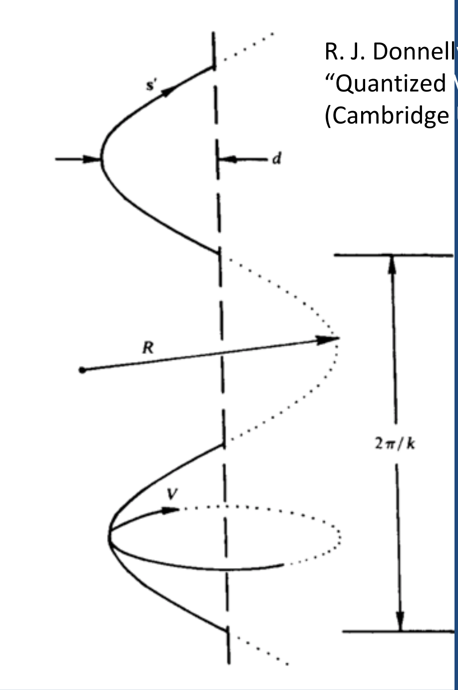
motivation : Quantum Turbulence & Kelvin wave

- **Kelvin wave**

Kelvin wave on the quantum vortex is very important role to understand the energy dissipation mechanism of the quantum turbulence at T=0 K.





R. J. Donnelly,
“Quantized Vortices in Helium II”
(Cambridge University Press,
Cambridge, 1991)

The wave length and eigenfrequency

wave number : $$k_K = \frac{2\pi n}{l_w} \qquad (n = 1,2,3\cdots)$$

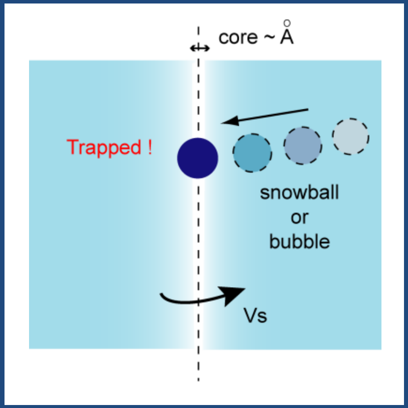
eigenfrequency : $$\varpi_k \sim \frac{\kappa \cdot k_k^2}{4\pi} \ln\left(\frac{1}{k_k a}\right)$$

l_w : vortex length, a : core radius

Can we observe the transition between laminar flow and the turbulence by well controlled Kelvin wave?

Motivation for this experiment

- The dissipation of Quantum Turbulence around T=0, no viscosity at all, is quite interesting problem.
- If it is possible for the ion to trap at the termination point of the vortex line, there is a possibility that we could drive the vortex line and excite the controlled Kelvin wave.



Today's talk

Topic : Transport property of Ions at Rest

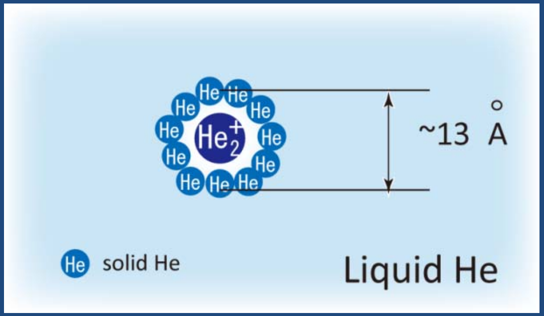
1. Recently, we found a unique transition between ohmic and non-ohmic current with increasing ac drive in 2D snowball system.
2. This transition remind us that new scattering mechanism arise except thermal roton, phonon, and ripplon.

We report recent experimental works about the critical velocity

introduction : Ions in Helium

- **Snowball**

Snowball : positive ion



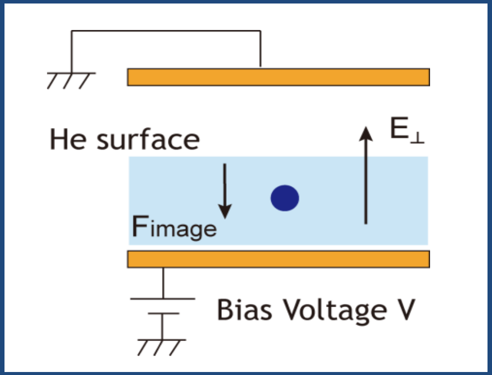
small cluster of solidified ^4He around a $^4He_2^+$ ion

radius **R_+ : 6~7 Å**

mass M_+ : **~30 m_{He} (T=0)**

m_{He} : bare helium mass

- **2D layer below surface**



Net vertical potential for ions

$$U(z) = eE_\perp z + \frac{e^2}{16\pi\varepsilon_0}\frac{\alpha-1}{\alpha(\alpha+1)}\frac{1}{z}$$

ion density

$n_s = \varepsilon_0 V_0 / e(D-d_l)$: $10^{11} \sim 10^{12}$ /m^2

Experiment

- ^{3}He impurity in liquid ^{4}He

- Ion mobility is limited by ^{3}He impurity
- Vortex core is easy to capture ^{3}He impurity

Commercial ^{4}He : x_{3He} ~ > 100ppb

Ultra isotropically Pure 4He

U.S. Bureau of Mines

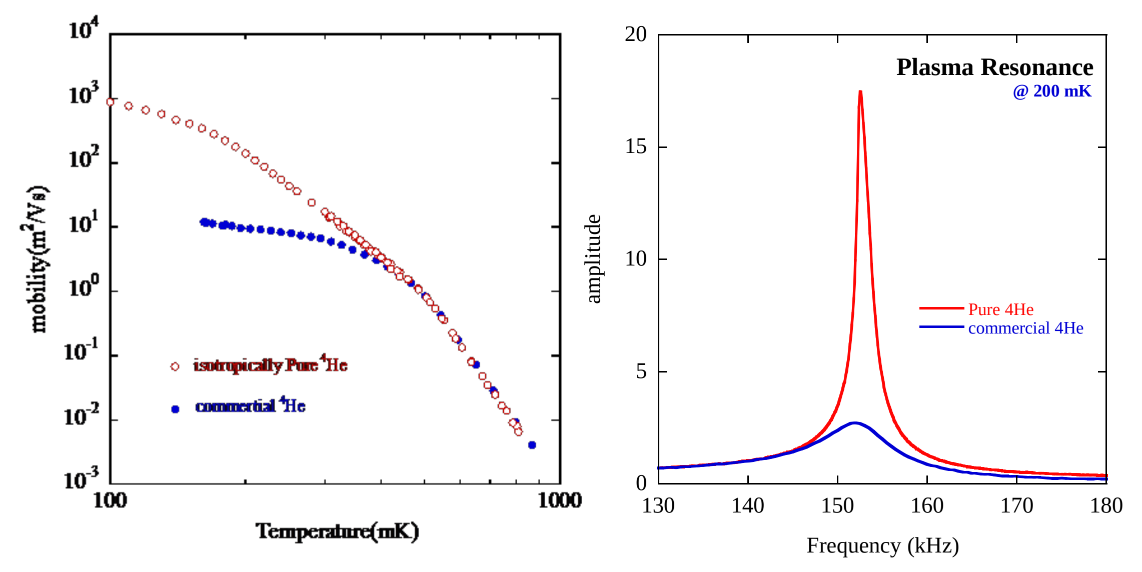
x_{3He} < 1ppb !!

Transport measurement of snowball

- **Conductivity**
  Limited below ~ 400 mK

- **Plasma Resonance**
  <pure 4He>
  Q-value ~ 5.2 larger

A few handled ppb x_{3He} : Serious effects on the transport properties



Experiment

- **Experimental parameters**
  - **Sommer – Tanner method**
  - **Measurement parameter**

    Input AC field - sin wave -

    $5\text{mV}_{pp} < V_{ac} < 5\ V_{pp}$

    30,020Hz < Freq
  - **Ion density**

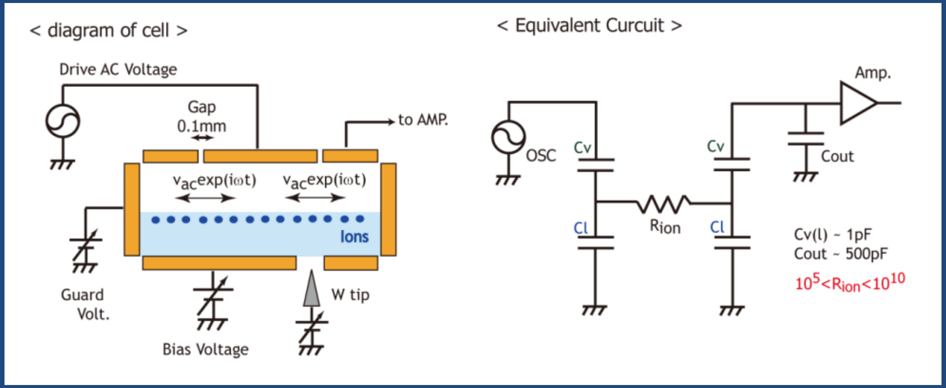
    Snowball used in this run

    Density : $6.6\text{x}10^{11}/\text{m}^2$
  - **Pressing Field & Distance**

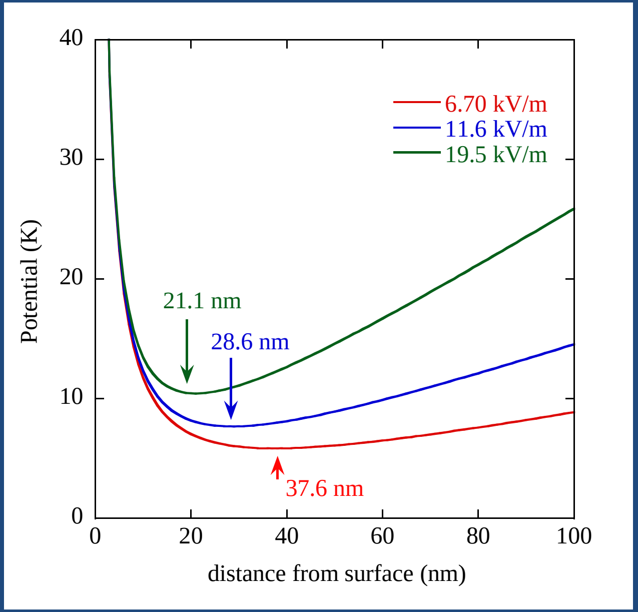
    $E_{\perp} = 6.70$ kV/m (**z = 37.6nm**)

    $E_{\perp} = 9.77$ kV/m (**z = 28.6nm**)

    $E_{\perp} = 11.6$ kV/m (**z = 21.1nm**)



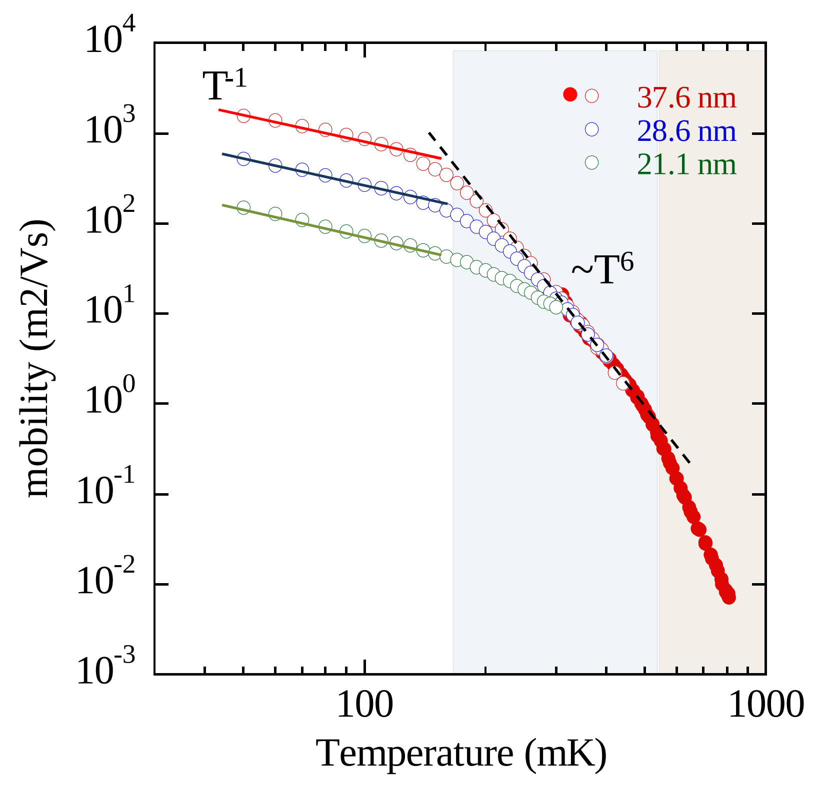
$$i_g = \frac{1}{G}\frac{C_{out}(C_V + C_l)}{C_V}\cdot \varpi V_{drive}\cdot\left|V_{output}\right|$$
$$= 2\pi r_i \cdot n_i e \cdot v_g$$



Result - Mobility Measurement

- **Temperature dependence of Mobility**

  Ion is driven by less than 5mVpp ac voltage



T> 550 mK

Scattered by thermal excited quasi particle

T < ~ 550 mK

Mobility is limited by **phonon limited μ**

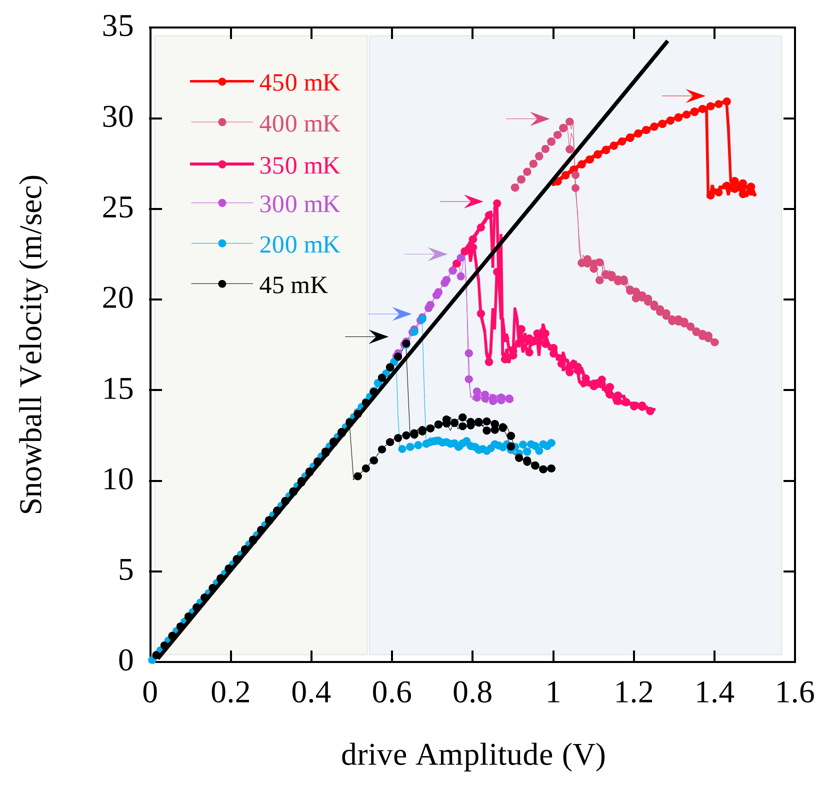
T < ~ 200 mK

Mobility is limited by **ripplon limited μ**

$\mu \propto 1/T$

Result – Critical Velocity(vc)

- **Drive voltage dependence of the snowball velocity**



Conditions : 37.6 nm
Freq. 50,020 Hz

1. below ~ 0.5 V
v_{ion} follows Ohm's law.

2. Above ~ 0.5 V
v_{ion} deviates from Ohm's law and shows the jump abruptly at threshold voltage.

3. T ~ 450 mK
v_{ion} strongly suppress before the jump.

Critical velocity shows the temperature dependence !

Result - Critical Velocity(vc)

- **Temperature dependence of v_c**

<parameters>
n_i = 6.6 x $10^{-11}/m^2$
Freq. : 50,020 Hz

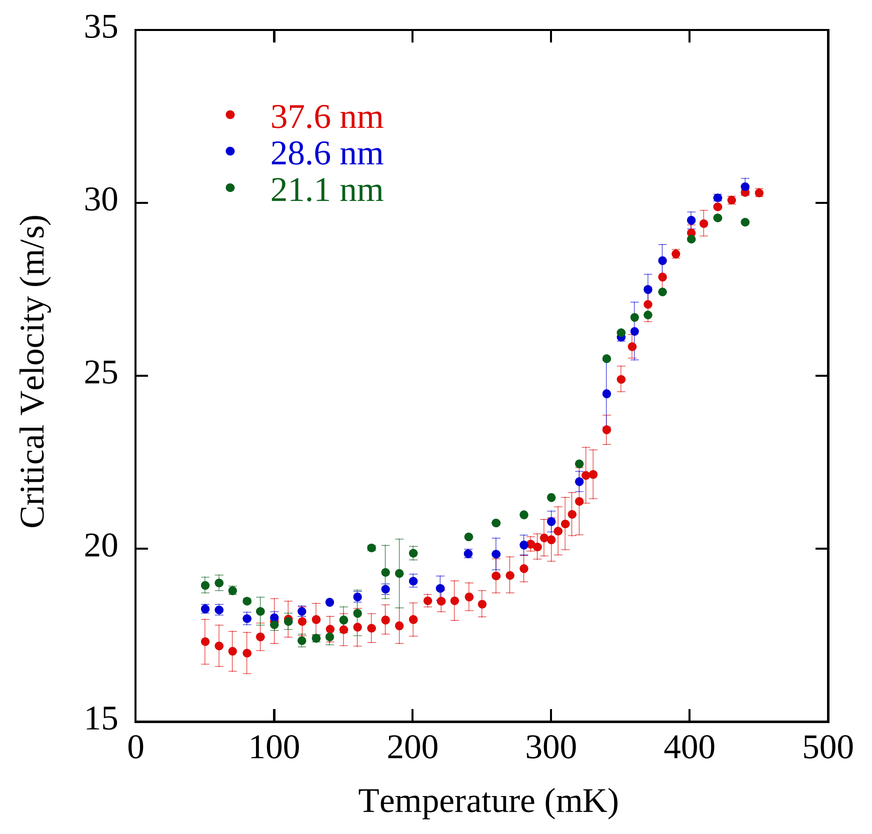
T > ~ 420 mK : $v_{c\ (high)}$ ~ 31 m/s

T< ~ 200 mK : $v_{c\ (low)}$ ~ 18 m/s

v_c decreases with decreasing temperature between these temperature.

ion mobility is strongly limited by ripplon scattering below 200 mK.

Vc is almost independent of the depth from the surface



Discussion

- The creation of vortex rings could be the origin of the nonlinear behavior.

Presumable vortex nucleation mechanism for bubble

Model : C. M. Muirhead et al.
Phil. Trans. R. Soc. Lond. A 331, 433(1984)

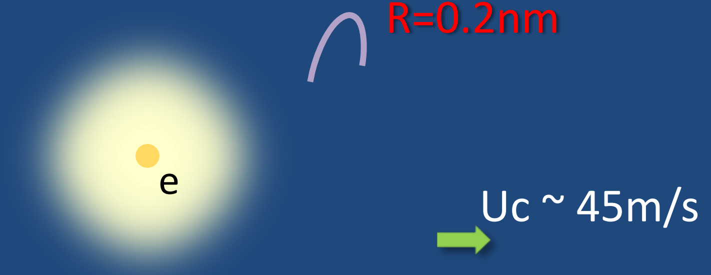
Experiment : G.G. Nacolas et al.
Phil. Trans. R. Soc. Lond. A313, 537(1985)

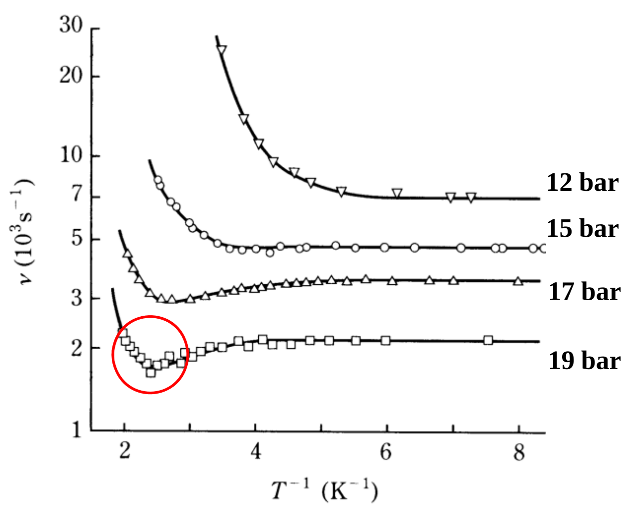
Macroscopic Quantum Tunneling

T=0 (K), P=0 (atm)

$U_c \sim 45$ (m/s)

$\Delta E \sim 0.5\times10^{-23}$ (J) ~ 3.6 (K)





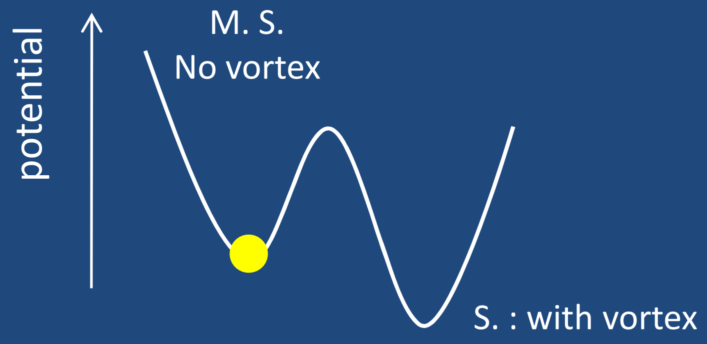
$$\nu(T) = \nu_0 \exp(-BT^3) + AT\exp(-\Delta/k_B T)$$

$$\underline{\Delta / k_B \sim 3(K)}$$

Discussion

- **Damping of nucleation rate : Caldeira-Leggett**

1. A small dip of ν(T) observed using electron bubble was thought that phonon damping reduces the tunneling rate.
2. In our case, v_c increased above ~200 mK. Temperature dependence of mobility shows that phonon scattering dominates the mobility above ~200 mK.



$$\nu_{nucl.} \propto \exp(-\underline{\sqrt{E_a}})*\exp(-B\eta)$$
$$= (WKB)*(dissipation\ \ term)$$

E_a : Energy barrier
η : Dissipation coefficient

Here, we introduce a phenomenological potential as follow

$$E_a = E_0 - aV_{ion}$$

Criterion for observation of tunneling

$$\nu_{nucl} \sim O(1)$$
$$\sim \exp(-\sqrt{E_0 - a\underline{\underline{V_c}}})*\exp(-\eta)$$

Discussion

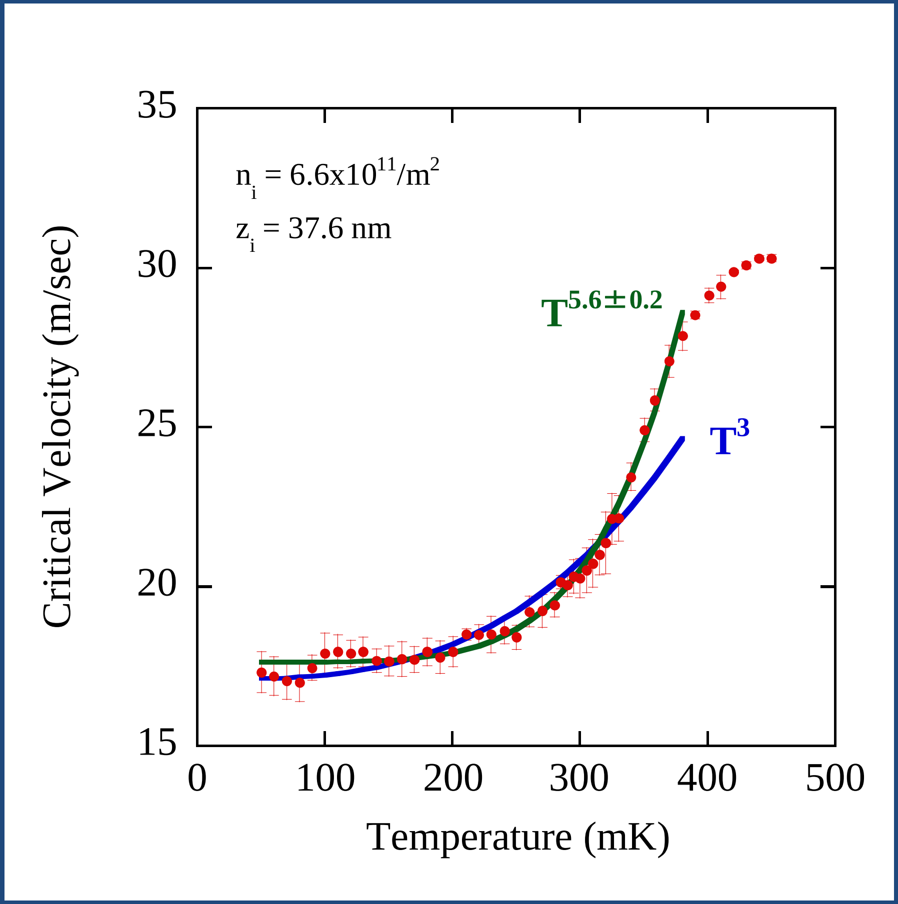
- **Critical velocity**

When we assume the energy barrier for tunneling as $E_0\text{-}aV_{ion}$. The critical velocity can be expressed as follows

$$V_c = V_0 + const.*\eta$$

η : Dissipation coefficient

The damping process is caused by phonon scattering, then η is expected in proportion to T^3.



The increase of v_c could be explained by the tunneling rate is reduced by some dissipation mechanism in this system.

Summary & Speculation

- We observed the critical velocity of the 2D ion systems underneath superfluid ^{4}He.
- The observed non-linear transport indicates that a new dissipation mechanism arises at critical velocity (v_c).
- v_c is sufficiently small (~60%) compared to Landau critical velocity for roton emission at saturated vapor pressure.
- **The nucleation of quantized vortex ring (q.v.r) could be the origin of the nonlinear behavior.**
- Below ~ 200 mK, temperature independent of vc means the macroscopic quantum tunneling rate of the nucleation of q.v.r. should be constant.
- On the other hand, below ~350 mK, the damping effect for the MQT by phonon may be important role to explain the increase of vc with increasing temperature
- Above ~350 mK, thermal activation process assists the q.v.r nucleation

Future Work

- We measure the critical velocity under rotation.