"Unsolved Problems" - A Celebration of Sir Tony Leggett's 80th Birthday, UIUC, Urbana IL, April 2, 2018

Signatures of Broken Symmetries in ^{3}He and Chiral Superconductors

J. A. Sauls

Northwestern University

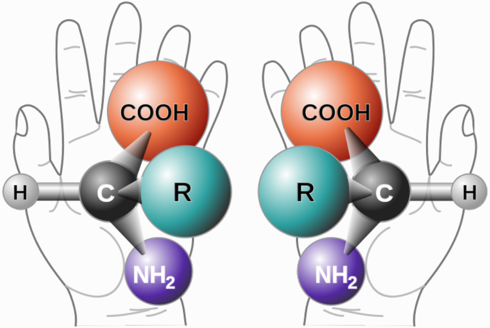
- Wave Ngampruetikorn • Oleksii Shevtsov • Joshua Wiman

- Broken P & T Symmetry - ^{3}He-A
- Edge Fermions & Left-Handed Electrons
- Anomalous Hall Effect in ^{3}He-A
- An Unsolved Problem ... or two

- Supported by National Science Foundation Grant DMR-1508730

Chirality in Nature

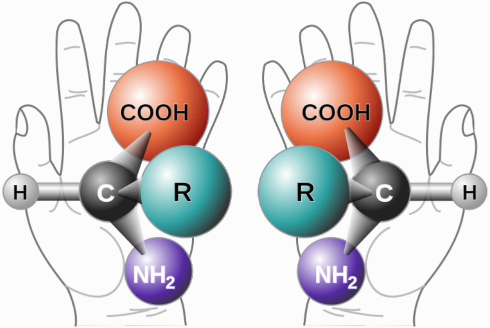
Molecular Chiral Enantiomers



Handedness: Broken Mirror Symmetry

Chirality in Nature

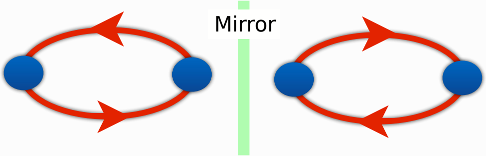
Molecular Chiral Enantiomers



Handedness: Broken Mirror Symmetry

Chiral Diatomic Molecules

$$\Psi(\mathbf{r}) = f(r)\,(x + iy)$$



Broken Mirror Symmetries

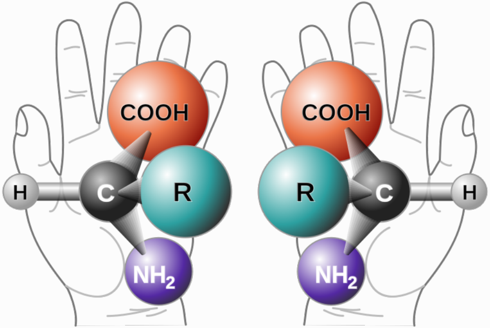
$$\Pi_{zx}\,\Psi(\mathbf{r}) = f(r)\,(x - iy)$$

Broken Time-Reversal Symmetry

$$\mathrm{T}\,\Psi(\mathbf{r}) = f(r)\,(x - iy)$$

Chirality in Nature

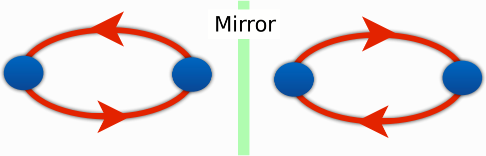
Molecular Chiral Enantiomers



Handedness: Broken Mirror Symmetry

Chiral Diatomic Molecules

$$\Psi(\mathbf{r}) = f(r)\,(x + iy)$$



Broken Mirror Symmetries

$$\Pi_{zx}\,\Psi(\mathbf{r}) = f(r)\,(x - iy)$$

Broken Time-Reversal Symmetry

$$\mathrm{T}\,\Psi(\mathbf{r}) = f(r)\,(x - iy)$$

Realized in Superfluid ^{3}He-A & possibly the ground states in unconventional superconductors

Chiral Superconductors

Ground states exhibiting:

- Emergent Topology of a Broken-Symmetry Vacuum of Cooper Pairs
- Weyl-Majorana excitations of the Vacuum
- Ground-State Edge Currents and Angular Momemtum
- Broken P and T $\rightsquigarrow$ Anomalous Hall Transport

Chiral Superconductors

Ground states exhibiting:

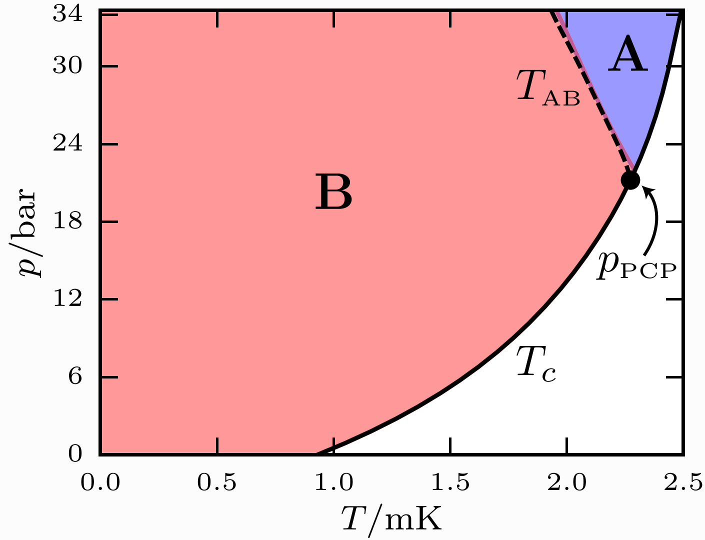
- Emergent Topology of a Broken-Symmetry Vacuum of Cooper Pairs
- Weyl-Majorana excitations of the Vacuum
- Ground-State Edge Currents and Angular Momemtum
- Broken P and T $\rightsquigarrow$ Anomalous Hall Transport

Where are They?

- ^{3}He-A: definitive chiral p-wave condensate; quantitative theory-experimental confirmation
- Sr_2RuO_4: proposed as the electronic analog of ^{3}He-A; evidence of chirality
- UPt_3: electronic analog to ^{3}He: Multiple Superconducting Phases; evidence of chirality
- Other candidates: URu_2Si_2; SrPtAs, doped graphene ...

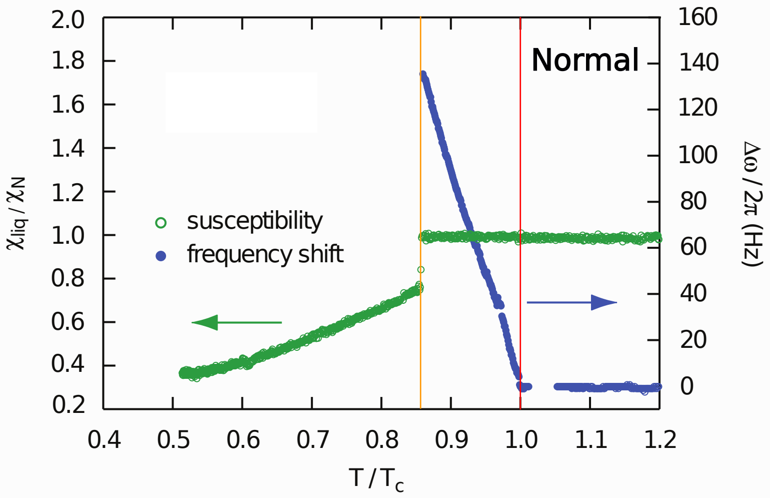
The Pressure-Temperature Phase Diagram for Liquid ^{3}He

Maximal Symmetry: $\mathtt{G} = \mathtt{SO(3)_S} \times \mathtt{SO(3)_L} \times \mathtt{U(1)_N} \times \mathtt{P} \times \mathtt{T} \rightarrow$ Superfluid Phases of ^{3}He



▶ J. Wiman & J. A. Sauls, PRB 92, 144515 (2015)

NMR frequency shift and Magnetic Susceptibility



Spin Dynamics and Broken Spin-Orbit Symmetry

VOLUME 29, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 1972

Interpretation of Recent Results on He^3 below 3 mK: A New Liquid Phase?

A. J. Leggett
School of Mathematical and Physical Sciences, University of Sussex, England
(Received 5 September 1972)

It is demonstrated that recent NMR results in ^3He indicate that at 2.65 mK, the liquid makes a second-order transition to a phase in which the "spin-orbit" symmetry is spontaneously broken. The hypothesis that this phase is a BCS-type phase in which pairs form with l odd, $S=1$, $S_z=\pm 1$ leads to reasonable agreement with both NMR and thermodynamic data, but involves some difficulties as to stability.

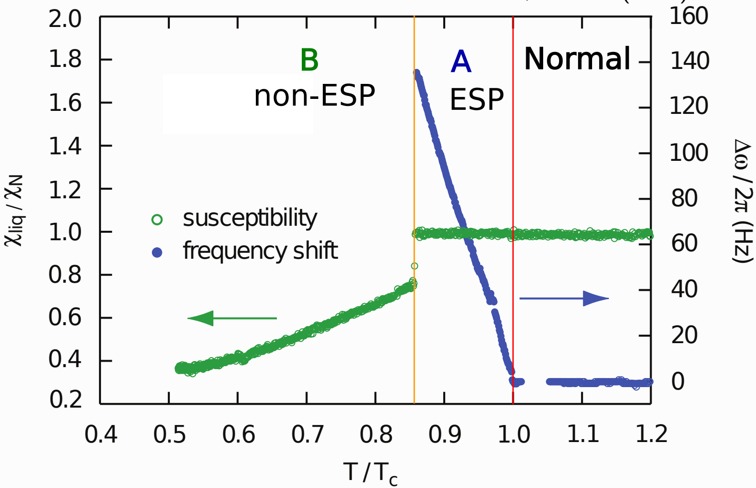
$$\omega^2 = (\gamma H)^2 + \Omega^2(T)$$

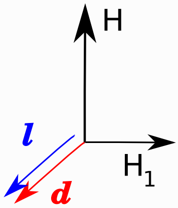
$$\Omega^2 = -\frac{2\gamma^2}{\chi}\langle \mathcal{H}_D \rangle \qquad \Omega \neq 0 \implies \text{Broken Spin-Orbit Symmetry}$$

$$\omega - \gamma H \simeq \frac{\Omega^2(T)}{2\gamma H} \propto (1 - T/T_c)$$

NMR frequency shift and Magnetic Susceptibility   Maximal Symmetry: $G = SO(3)_S \times SO(3)_L \times U(1)_N \times P \times T$

J. Pollanen et al. PRL 107, 195301 (2011)





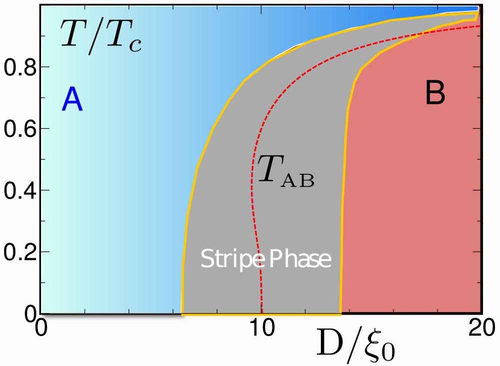
- $\mathbf{d}_B(\mathbf{p}) = \Delta_B(T) \left(\hat{p}_x \hat{\mathbf{d}}_x + \hat{p}_y \hat{\mathbf{d}}_y + \hat{p}_z \hat{\mathbf{d}}_z\right)$
  $\rightsquigarrow G \to SO(3)_J \times T$
- $\mathbf{d}_A(\mathbf{p}) = \Delta_A(T)\, \hat{\mathbf{d}}\, (\hat{p}_x + i\hat{p}_y)$
  $\rightsquigarrow G \to SO(2)_S \times U(1)_{L_z - N} \times Z_2$

Realization of Broken Time-Reversal and Mirror Symmetry by the Vacuum State of ^{3}He Films

- Length Scale for Strong Confinement:

  $\xi_0 = \hbar v_f / 2\pi k_B T_c \approx 20 - 80\,\text{nm}$

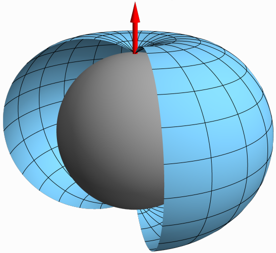
  - L. Levitov et al., Science 340, 6134 (2013)
- A. Vorontsov & J. A. Sauls, PRL 98, 045301 (2007)



$$\begin{pmatrix} \Psi_{\uparrow\uparrow} & \Psi_{\uparrow\downarrow} \\ \Psi_{\uparrow\downarrow} & \Psi_{\downarrow\downarrow} \end{pmatrix}_{ABM} = \begin{pmatrix} p_x + ip_y \sim e^{+i\phi} & 0 \\ 0 & p_x + ip_y \sim e^{+i\phi} \end{pmatrix}$$

$$\text{SO(3)}_\text{S} \times \text{SO(3)}_\text{L} \times \text{U(1)}_\text{N} \times \text{T} \times \text{P}$$
$$\Downarrow$$
$$\text{SO(2)}_\text{S} \times \text{U(1)}_{\text{N-L}_z} \times \text{Z}_2$$

Chiral ABM State $\vec{l} = \hat{\mathbf{z}}$



$L_z = 1,\ S_z = 0$

Ground-State Angular Momentum

$\langle \widehat{L}_z \rangle = \frac{N}{2}\hbar$?

Open Question

Signatures of Broken T and P Symmetry in ^{3}He-A

What is the Evidence for Chirality of Superfluid ^{3}He-A?

Signatures of Broken T and P Symmetry in ^{3}He-A

What is the Evidence for Chirality of Superfluid ^{3}He-A?

Broken T and P $\rightsquigarrow$ Anomalous Hall Effect for Electrons in ^{3}He-A

Signatures of Broken T and P Symmetry in ^{3}He-A

What is the Evidence for Chirality of Superfluid ^{3}He-A?

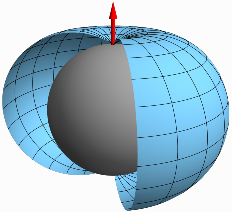
Broken T and P $\rightsquigarrow$ Anomalous Hall Effect for Electrons in ^{3}He-A

Broken Symmetries $\rightsquigarrow$ Topology of ^{3}He-A

Chirality $+$ Topology $\rightsquigarrow$ Chiral Edge States

Topology in Momentum Space

$$\Psi(\mathbf{p}) = \Delta(p_x \pm i p_y) \sim e^{\pm i\varphi_{\mathbf{p}}}$$



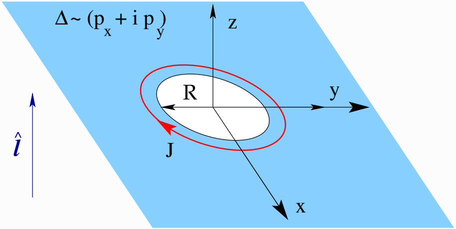
Winding Number of the Phase:

$$L_z = \pm 1$$

$$N_{\text{2D}} = \frac{1}{2\pi} \oint d\mathbf{p} \cdot \frac{1}{|\Psi(\mathbf{p})|} \text{Im}[\boldsymbol{\nabla}_{\mathbf{p}} \Psi(\mathbf{p})] = L_z$$

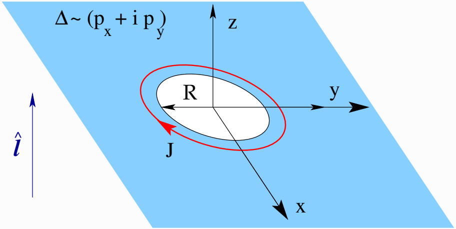
- Massless Chiral Fermions
  - Nodal Fermions in 3D
  - Edge Fermions in 2D

Chiral Edge Current Circulating a Hole or Defect in a Chiral Superfluid



- $R \gg \xi_0 \approx 100\,\text{nm}$
- Sheet Current:
  $$J \equiv \int dx\, J_{\varphi}(x)$$

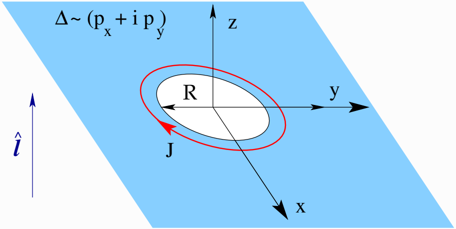
Chiral Edge Current Circulating a Hole or Defect in a Chiral Superfluid



- $R \gg \xi_0 \approx 100\,\text{nm}$
- Sheet Current:
  $J \equiv \int dx\, J_\varphi(x)$

- Quantized Sheet Current: $\frac{1}{4}\, n\, \hbar$ $(n = N/V = {}^3\text{He density})$
- Edge Current *Counter*-Circulates: $J = -\frac{1}{4}\, n\, \hbar$ w.r.t. Chirality: $\hat{\mathbf{l}} = +\mathbf{z}$

Chiral Edge Current Circulating a Hole or Defect in a Chiral Superfluid



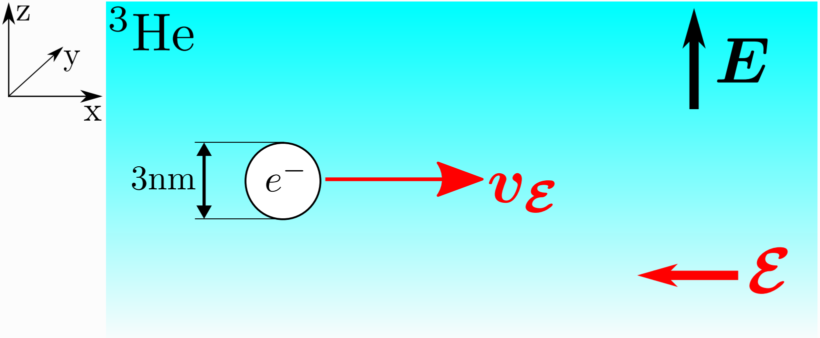
- $R \gg \xi_0 \approx 100\,\text{nm}$
- Sheet Current : $J \equiv \int dx\, J_\varphi(x)$

- Quantized Sheet Current: $\frac{1}{4}\, n\, \hbar$ $(n = N/V = {}^3\text{He density})$
- Edge Current *Counter*-Circulates: $J = -\frac{1}{4}\, n\, \hbar$ w.r.t. Chirality: $\hat{\mathbf{l}} = +\mathbf{z}$
- Angular Momentum: $L_z = 2\pi\, h\, R^2 \times (-\frac{1}{4}\, n\, \hbar) = -(N_{\text{hole}}/2)\, \hbar$

$N_{\text{hole}}/2 =$ Number of ^{3}He Cooper Pairs excluded from the Hole

∴ An object in ^{3}He-A *inherits* angular momentum from the Condensate of Chiral Pairs!

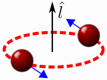
Electron bubbles in the Normal Fermi liquid phase of ^{3}He



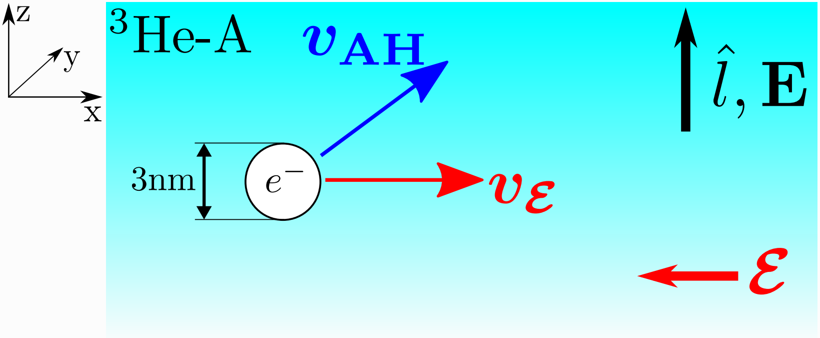
- Bubble with $R \simeq 1.5$ nm, $0.1\,\text{nm} \simeq \lambda_f \ll R \ll \xi_0 \simeq 80\,\text{nm}$
- Effective mass $M \simeq 100 m_3$ (m_3 – atomic mass of ^{3}He)
- QPs mean free path $l \gg R$
- Mobility of ^{3}He is *independent of* T for $T_c < T < 50$ mK

B. Josephson and J. Leckner, PRL 23, 111 (1969)

Electron bubbles in chiral superfluid ^{3}He-A

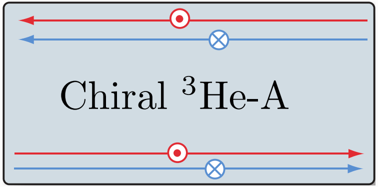


$\Delta(\hat{k}) = \Delta(\hat{k}_x + i\hat{k}_y) = \Delta\, e^{i\phi_{\mathbf{k}}}$

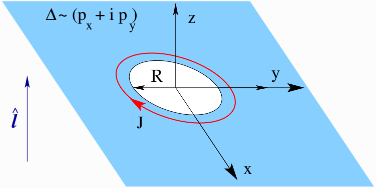


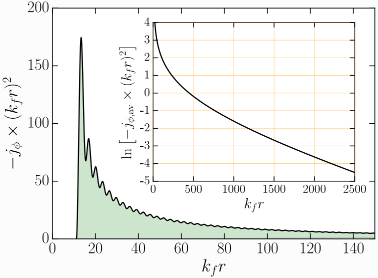
- Current: $\mathbf{v} = \overbrace{\mu_\perp \boldsymbol{\mathcal{E}}}^{\mathbf{v}_{\mathcal{E}}} + \overbrace{\mu_{\mathsf{AH}} \boldsymbol{\mathcal{E}} \times \hat{\mathbf{l}}}^{\mathbf{v}_{\mathsf{AH}}}$ R. Salmelin, M. Salomaa & V. Mineev, PRL **63**, 868 (1989)
- Hall ratio: $\tan\alpha = v_{\mathsf{AH}}/v_{\mathcal{E}} = |\mu_{\mathsf{AH}}/\mu_\perp|$

Current bound to an electron bubble ($k_f R = 11.17$)

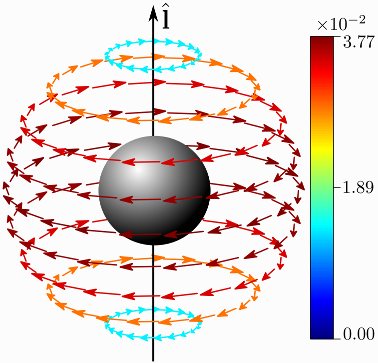


$\Longrightarrow$





$\Longrightarrow$

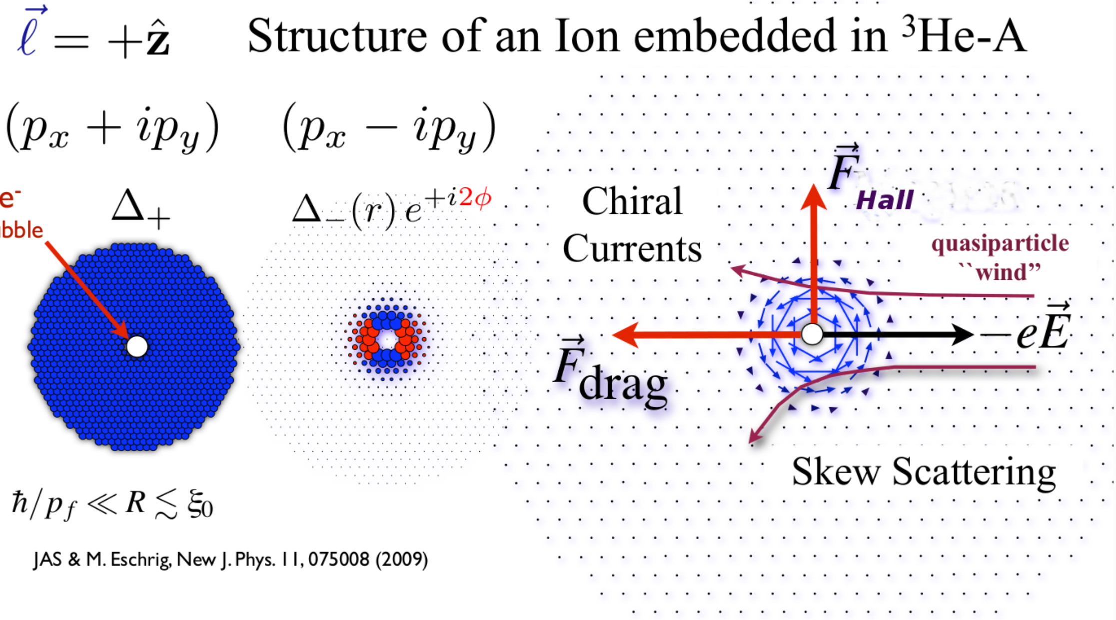


$$\mathbf{j}(\mathbf{r})/v_f N_f k_B T_c = j_\phi(\mathbf{r})\hat{\mathbf{e}}_\phi$$

- O. Shevtsov and JAS, Phys. Rev. B 96, 064511 (2016)

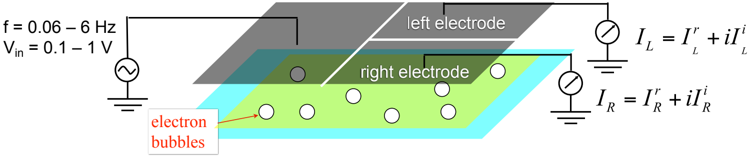
$$\mathbf{L}(T \to 0) \approx -\hbar N_{\mathrm{bubble}}/2\,\hat{\mathbf{l}} \approx -100\,\hbar\,\hat{\mathbf{l}}$$

Skew Scattering of Quasiparticles by Bubble Edge Currents



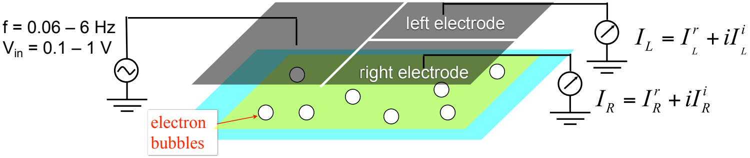
JAS & M. Eschrig, New J. Phys. 11, 075008 (2009)

Measurement of the Transverse e⁻ mobility in Superfluid ^{3}He Films



H. Ikegami, Y. Tsutsumi, K. Kono, Science 341, 59-62 (2013)

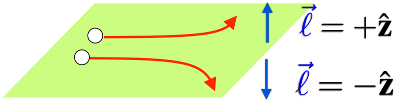
Measurement of the Transverse e⁻ mobility in Superfluid ^{3}He Films



Transverse Force from ***Skew* Scattering**

$$\rightsquigarrow \quad \Delta I = I_R - I_L \neq 0$$

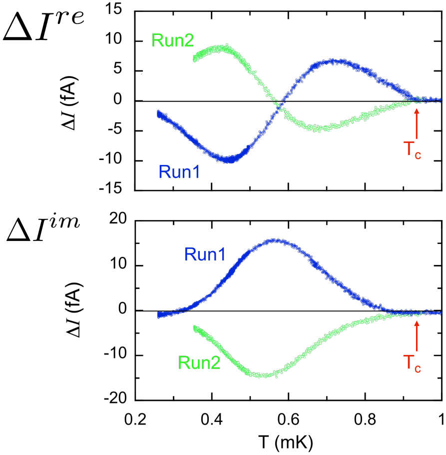
$$\vec{v} = \left[\mu_\perp \vec{E} + \mu_{xy}\,\hat{\ell} \times \vec{E}\right]$$

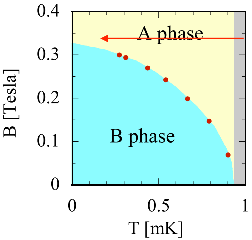


H. Ikegami, Y. Tsutsumi, K. Kono, Science 341, 59-62 (2013)

Transverse e⁻ bubble current in ^{3}He-A

$$\Delta I = I_R - I_L$$





Single Domains:

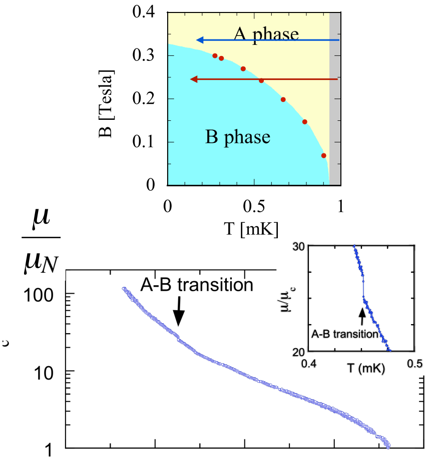
Run 1 $\vec{\ell} = +\hat{\mathbf{z}}$

Run 2 $\vec{\ell} = -\hat{\mathbf{z}}$

$$\frac{|I_R - I_L|}{I_R + I_L} \approx 6\,\%$$

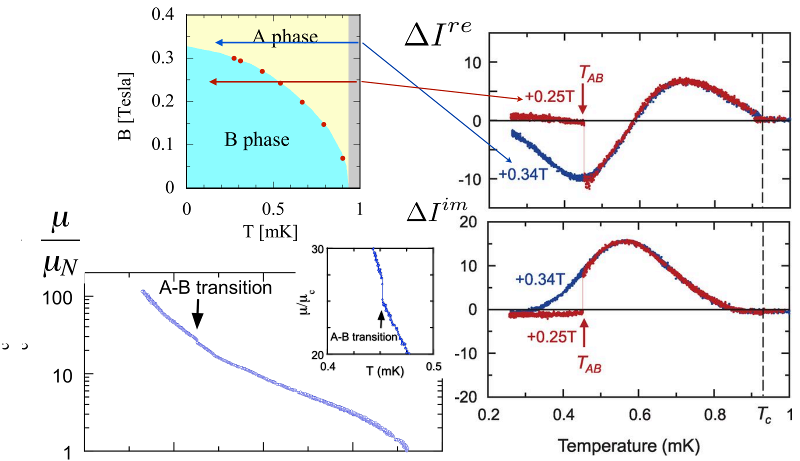
H. Ikegami, Y. Tsutsumi, K. Kono, Science 341, 59-62 (2013)

Zero **Transverse e^{-} current in ^{3}He-B (*T - symmetric phase*)**



H. Ikegami, Y. Tsutsumi, K. Kono, Science 341, 59-62 (2013)

Zero Transverse e$^-$ current in ^{3}He-B (*T - symmetric phase*)



H. Ikegami, Y. Tsutsumi, K. Kono, Science 341, 59-62 (2013)

Forces on the Electron bubble in ^{3}He-A:

- $M\frac{d\mathbf{v}}{dt} = e\boldsymbol{\mathcal{E}} + \mathbf{F}_{\mathrm{QP}}$, $\mathbf{F}_{QP}$ – force from quasiparticle collisions

Forces on the Electron bubble in ^{3}He-A:

- $M\frac{d\mathbf{v}}{dt} = e\boldsymbol{\mathcal{E}} + \mathbf{F}_{\mathrm{QP}}$, $\mathbf{F}_{QP}$ – force from quasiparticle collisions
- $\mathbf{F}_{QP} = -\overset{\leftrightarrow}{\eta} \cdot \mathbf{v}$, $\overset{\leftrightarrow}{\eta}$ – generalized Stokes tensor
- $\overset{\leftrightarrow}{\eta} = \begin{pmatrix} \eta_\perp & \eta_{\mathsf{AH}} & 0 \\ -\eta_{\mathsf{AH}} & \eta_\perp & 0 \\ 0 & 0 & \eta_\parallel \end{pmatrix}$ for broken PT symmetry with $\hat{\mathbf{l}} \parallel \mathbf{e}_z$

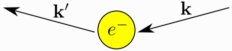
Forces on the Electron bubble in ^{3}He-A:

- $M\frac{d\mathbf{v}}{dt} = e\boldsymbol{\mathcal{E}} + \mathbf{F}_{\mathrm{QP}}$, $\mathbf{F}_{QP}$ – force from quasiparticle collisions
- $\mathbf{F}_{QP} = -\overleftrightarrow{\eta}\cdot\mathbf{v}$, $\overleftrightarrow{\eta}$ – generalized Stokes tensor
- $\overleftrightarrow{\eta} = \begin{pmatrix} \eta_\perp & \eta_{\mathsf{AH}} & 0 \\ -\eta_{\mathsf{AH}} & \eta_\perp & 0 \\ 0 & 0 & \eta_\parallel \end{pmatrix}$ for broken PT symmetry with $\hat{\mathbf{l}} \parallel \mathbf{e}_z$
- $M\frac{d\mathbf{v}}{dt} = e\boldsymbol{\mathcal{E}} - \eta_\perp\mathbf{v} + \frac{e}{c}\mathbf{v}\times\mathbf{B}_{\mathrm{eff}}$, for $\boldsymbol{\mathcal{E}} \perp \hat{\mathbf{l}}$
- $\mathbf{B}_{\mathrm{eff}} = -\frac{c}{e}\eta_{\mathsf{AH}}\hat{\mathbf{l}}$ $\quad B_{\mathrm{eff}} \simeq 10^3 - 10^4\ \mathrm{T}$!!!

Forces on the Electron bubble in ^{3}He-A:

- $M\frac{d\mathbf{v}}{dt} = e\boldsymbol{\mathcal{E}} + \mathbf{F}_{\mathrm{QP}}$, $\mathbf{F}_{QP}$ – force from quasiparticle collisions
- $\mathbf{F}_{QP} = -\overleftrightarrow{\eta} \cdot \mathbf{v}$, $\overleftrightarrow{\eta}$ – generalized Stokes tensor
- $\overleftrightarrow{\eta} = \begin{pmatrix} \eta_\perp & \eta_{\mathsf{AH}} & 0 \\ -\eta_{\mathsf{AH}} & \eta_\perp & 0 \\ 0 & 0 & \eta_\parallel \end{pmatrix}$ for broken PT symmetry with $\hat{\mathbf{l}} \parallel \mathbf{e}_z$
- $M\frac{d\mathbf{v}}{dt} = e\boldsymbol{\mathcal{E}} - \eta_\perp \mathbf{v} + \frac{e}{c}\mathbf{v} \times \mathbf{B}_{\mathrm{eff}}$, for $\boldsymbol{\mathcal{E}} \perp \hat{\mathbf{l}}$
- $\mathbf{B}_{\mathrm{eff}} = -\frac{c}{e}\eta_{\mathsf{AH}}\hat{\mathbf{l}}$ $\quad B_{\mathrm{eff}} \simeq 10^3 - 10^4\ \mathrm{T}$!!!
- Mobility: $\frac{d\mathbf{v}}{dt} = 0 \quad \rightsquigarrow \quad \mathbf{v} = \overleftrightarrow{\mu}\boldsymbol{\mathcal{E}}$, where $\overleftrightarrow{\mu} = e\overleftrightarrow{\eta}^{-1}$

T-matrix description of Quasiparticle-Ion scattering



- Lippmann-Schwinger equation for the T-matrix ($\varepsilon = E + i\eta\,;\ \eta \to 0^+$):

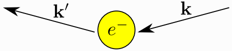
$$\hat{T}_S^R(\mathbf{k}', \mathbf{k}, E) = \hat{T}_N^R(\mathbf{k}', \mathbf{k}) + \int \frac{d^3k''}{(2\pi)^3} \hat{T}_N^R(\mathbf{k}', \mathbf{k}'')\Big[\hat{G}_S^R(\mathbf{k}'', E) - \hat{G}_N^R(\mathbf{k}'', E)\Big]\hat{T}_S^R(\mathbf{k}'', \mathbf{k}, E)$$

$$\hat{G}_S^R(\mathbf{k}, E) = \frac{1}{\varepsilon^2 - E_{\mathbf{k}}^2} \begin{pmatrix} \varepsilon + \xi_k & -\Delta(\hat{\mathbf{k}}) \\ -\Delta^\dagger(\hat{\mathbf{k}}) & \varepsilon - \xi_k \end{pmatrix}, \quad E_{\mathbf{k}} = \sqrt{\xi_k^2 + |\Delta(\hat{\mathbf{k}})|^2}, \ \ \xi_k = \frac{\hbar^2 k^2}{2m^*} - \mu$$

- Normal-state T-matrix:

$$\hat{T}_N^R(\hat{\mathbf{k}}', \hat{\mathbf{k}}) = \begin{pmatrix} t_N^R(\hat{\mathbf{k}}', \hat{\mathbf{k}}) & 0 \\ 0 & -[t_N^R(-\hat{\mathbf{k}}', -\hat{\mathbf{k}})]^\dagger \end{pmatrix} \quad \text{in p-h (Nambu) space}$$

T-matrix description of Quasiparticle-Ion scattering



- Lippmann-Schwinger equation for the T-matrix ($\varepsilon = E + i\eta\,;\ \eta \to 0^+$):

$$\hat{T}^R_S(\mathbf{k}', \mathbf{k}, E) = \hat{T}^R_N(\mathbf{k}', \mathbf{k}) + \int \frac{d^3k''}{(2\pi)^3} \hat{T}^R_N(\mathbf{k}', \mathbf{k}'') \Big[\hat{G}^R_S(\mathbf{k}'', E) - \hat{G}^R_N(\mathbf{k}'', E)\Big] \hat{T}^R_S(\mathbf{k}'', \mathbf{k}, E)$$

$$\hat{G}^R_S(\mathbf{k}, E) = \frac{1}{\varepsilon^2 - E^2_{\mathbf{k}}} \begin{pmatrix} \varepsilon + \xi_k & -\Delta(\hat{\mathbf{k}}) \\ -\Delta^\dagger(\hat{\mathbf{k}}) & \varepsilon - \xi_k \end{pmatrix}, \quad E_{\mathbf{k}} = \sqrt{\xi_k^2 + |\Delta(\hat{\mathbf{k}})|^2}, \ \ \xi_k = \frac{\hbar^2 k^2}{2m^*} - \mu$$

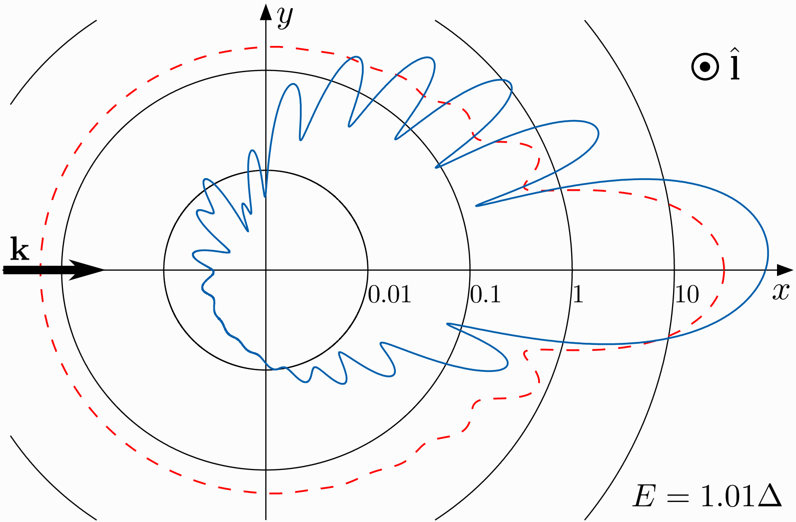
- Normal-state T-matrix:

$$\hat{T}^R_N(\hat{\mathbf{k}}', \hat{\mathbf{k}}) = \begin{pmatrix} t^R_N(\hat{\mathbf{k}}', \hat{\mathbf{k}}) & 0 \\ 0 & -[t^R_N(-\hat{\mathbf{k}}', -\hat{\mathbf{k}})]^\dagger \end{pmatrix}$$ in p-h (Nambu) space, where

$$t^R_N(\hat{\mathbf{k}}', \hat{\mathbf{k}}) = -\frac{1}{\pi N_f} \sum_{l=0}^{\infty} (2l+1) e^{i\delta_l} \sin\delta_l P_l(\hat{\mathbf{k}}' \cdot \hat{\mathbf{k}}), \quad P_l(x)$$ – Legendre function

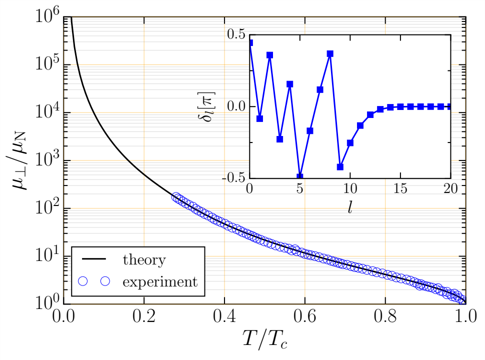
- Hard-sphere potential $\rightsquigarrow \tan\delta_l = j_l(k_f R)/n_l(k_f R)$ – spherical Bessel functions
  - $k_f R$ – determined by the Normal-State Mobility $\rightsquigarrow$ $k_f R = 11.17\ (R = 1.42\,\text{nm})$

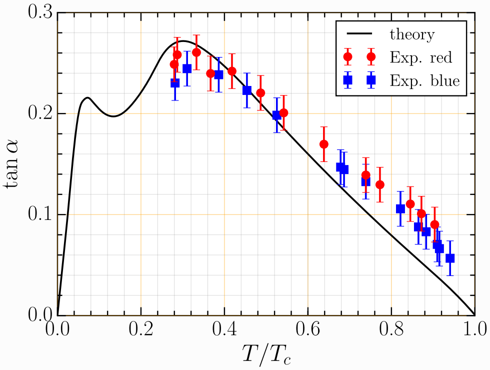
Differential cross section for Bogoliubov QP-Ion Scattering $k_f R = 11.17$



▶ O. Shevtsov and JAS, Phys. Rev. B 96, 064511 (2016)

Comparison between Theory and Experiment for the Drag and Transverse Forces





- $\mu_\perp = e\,\dfrac{\eta_\perp}{\eta_\perp^2 + \eta_{AH}^2}$
- $\mu_{AH} = -e\,\dfrac{\eta_{AH}}{\eta_\perp^2 + \eta_{AH}^2}$

- $\tan\alpha = \left|\dfrac{\mu_{AH}}{\mu_\perp}\right| = \dfrac{\eta_{AH}}{\eta_\perp}$
- Hard-Sphere Model: $k_f R = 11.17$

- O. Shevtsov and JAS, Phys. Rev. B 96, 064511 (2016)
- O. Shevtsov and JAS, JLTP 187, 340353 (2017)

Summary

- Electrons in ^{3}He-A are "dressed" by a spectrum of Chiral Fermions
- Electrons in ^{3}He-A are "Left handed" in a Right-handed Chiral Vacuum
  $\rightsquigarrow L_z \approx -(N_{bubble}/2)\hbar \approx -100\,\hbar$
- Experiment: RIKEN mobility experiments $\rightsquigarrow$ Observation an AHE in ^{3}He-A
- Scattering of Bogoliubov QPs by the dressed Ion
  $\rightsquigarrow$ Drag Force $(-\eta_{\perp}\mathbf{v})$ and Transverse Force $(\frac{e}{c}\mathbf{v} \times \mathbf{B}_{eff})$ on the Ion
- *Anomalous Hall Field:* $\mathbf{B}_{\text{eff}} \approx \frac{\Phi_0}{3\pi^2}\, k_f^2\, (k_f R)^2 \left(\frac{\eta_{\text{AH}}}{\eta_{\text{N}}}\right) \mathbf{l} \simeq 10^3 - 10^4\,\text{T}\,\mathbf{l}$
- Mechanism: Skew/Andreev Scattering of Bogoliubov QPs by the dressed Ion
- Origin: Broken Mirror & Time-Reversal Symmetry $\rightsquigarrow W(\mathbf{k},\mathbf{k}') \neq W(\mathbf{k}',\mathbf{k})$
- Theory: $\rightsquigarrow$ Quantitative account of RIKEN mobility experiments

Summary

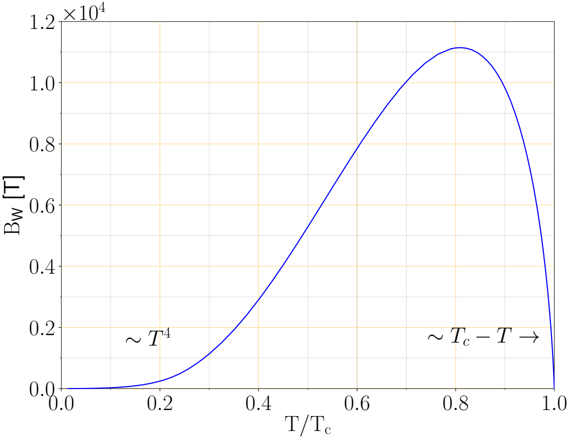
- Electrons in ^{3}He-A are "dressed" by a spectrum of Chiral Fermions
- Electrons in ^{3}He-A are "Left handed" in a Right-handed Chiral Vacuum
  $\rightsquigarrow L_z \approx -(N_{bubble}/2)\hbar \approx -100\,\hbar$
- Experiment: RIKEN mobility experiments $\rightsquigarrow$ Observation an AHE in ^{3}He-A
- Scattering of Bogoliubov QPs by the dressed Ion
  $\rightsquigarrow$ Drag Force $(-\eta_{\perp}\mathbf{v})$ and Transverse Force $(\frac{e}{c}\mathbf{v} \times \mathbf{B}_{eff})$ on the Ion
- *Anomalous Hall Field:* $\mathbf{B}_{\text{eff}} \approx \frac{\Phi_0}{3\pi^2}\, k_f^2\, (k_f R)^2 \left(\frac{\eta_{\text{AH}}}{\eta_{\text{N}}}\right) \mathbf{l} \simeq 10^3 - 10^4\,\text{T}\,\mathbf{l}$
- Mechanism: Skew/Andreev Scattering of Bogoliubov QPs by the dressed Ion
- Origin: Broken Mirror & Time-Reversal Symmetry $\rightsquigarrow W(\mathbf{k},\mathbf{k}') \neq W(\mathbf{k}',\mathbf{k})$
- Theory: $\rightsquigarrow$ Quantitative account of RIKEN mobility experiments
- Open Problem: Theory of Radiation Dominated Motion of Electrons in a Chiral Vacuum

Summary

- Electrons in ^{3}He-A are "dressed" by a spectrum of Chiral Fermions
- Electrons in ^{3}He-A are "Left handed" in a Right-handed Chiral Vacuum
  $\rightsquigarrow L_z \approx -(N_{bubble}/2)\hbar \approx -100\,\hbar$
- Experiment: RIKEN mobility experiments $\rightsquigarrow$ Observation an AHE in ^{3}He-A
- Scattering of Bogoliubov QPs by the dressed Ion
  $\rightsquigarrow$ Drag Force $(-\eta_\perp \mathbf{v})$ and Transverse Force $(\frac{e}{c}\mathbf{v} \times \mathbf{B}_{eff})$ on the Ion
- *Anomalous Hall Field:* $\mathbf{B}_{\text{eff}} \approx \frac{\Phi_0}{3\pi^2} k_f^2 (k_f R)^2 \left(\frac{\eta_{\text{AH}}}{\eta_{\text{N}}}\right) \mathbf{l} \simeq 10^3 - 10^4\,\text{T}\,\mathbf{l}$
- Mechanism: Skew/Andreev Scattering of Bogoliubov QPs by the dressed Ion
- Origin: Broken Mirror & Time-Reversal Symmetry $\rightsquigarrow W(\mathbf{k},\mathbf{k}') \neq W(\mathbf{k}',\mathbf{k})$
- Theory: $\rightsquigarrow$ Quantitative account of RIKEN mobility experiments
- Open Problem: Theory of Radiation Dominated Motion of Electrons in a Chiral Vacuum
- Open Problem: Bulk Signature of BTRS in UPt_3,Sr_2RuO_4 $\rightsquigarrow$ Thermal Hall Effects?

Vanishing of the Effective Magnetic Field for $T \to 0$

$$B_W = 5.9 \times 10^5\ \mathrm{T} \left(\frac{\eta_{xy}}{\eta_N}\right)$$

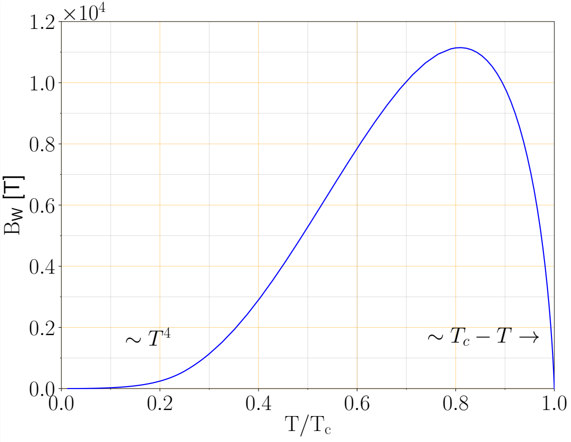


$$\eta_{xy}/\eta_N|_{T=0.8\,T_c} \approx \frac{\hbar}{p_f R}$$

Breakdown of Laminar Flow

Vanishing of the Effective Magnetic Field for $T \to 0$

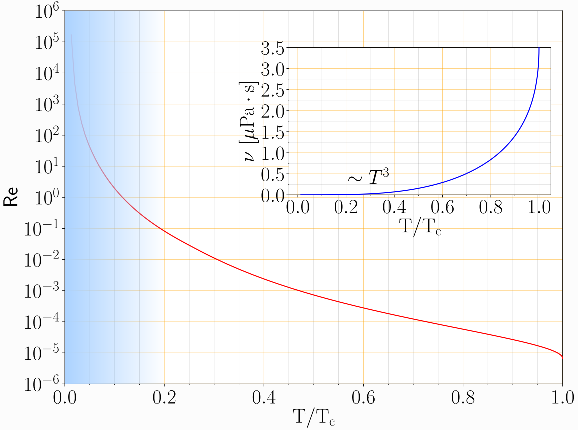
$$B_{\mathsf{W}} = \boxed{5.9 \times 10^5\ \mathsf{T}} \left(\frac{\eta_{xy}}{\eta_{\mathsf{N}}} \right)$$



$$\eta_{xy}/\eta_{\mathsf{N}}|_{T=0.8\,T_c} \approx \frac{\hbar}{p_f R}$$

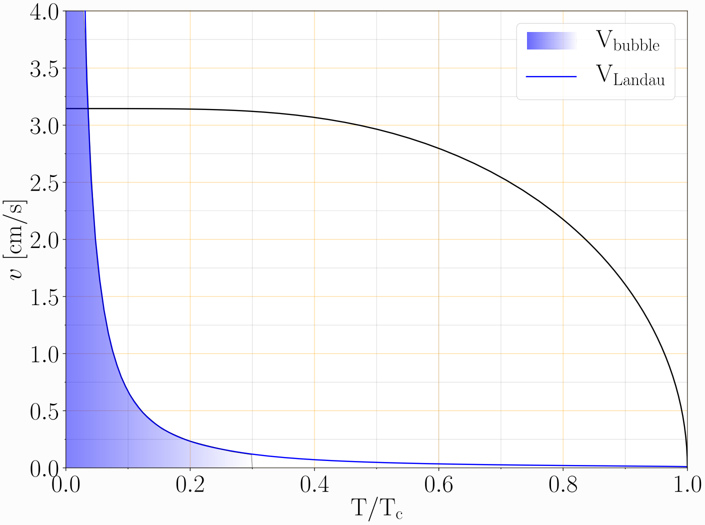
Breakdown of Laminar Flow

$$\mathsf{Re} = \mathsf{Re}_{\mathsf{N}} \left(\frac{\eta_{\mathsf{N}}}{\eta} \right)^{3/2} \xrightarrow[T\to 0]{} \sim \left(\frac{T_c}{T} \right)^{9/2}$$



$$\mathsf{Re}_{\mathsf{N}} = 6.7 \times 10^{-6}$$

Breakdown of Scattering Theory for $T \to 0$



Electron Bubble Velocity

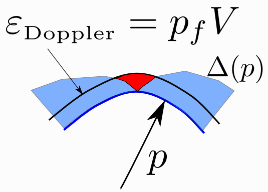
- $V_N = \mu_N E_N = 1.01 \times 10^{-4}$m/s
- $V = \mu_N E_N \sqrt{\frac{\eta_N}{\eta}}$

Maximum Landau critical velocity

- $V_c^{max} \approx 155 \times 10^{-4}$m/s $\frac{\Delta_A(T)}{k_b T_c}$

Nodal Superfluids:

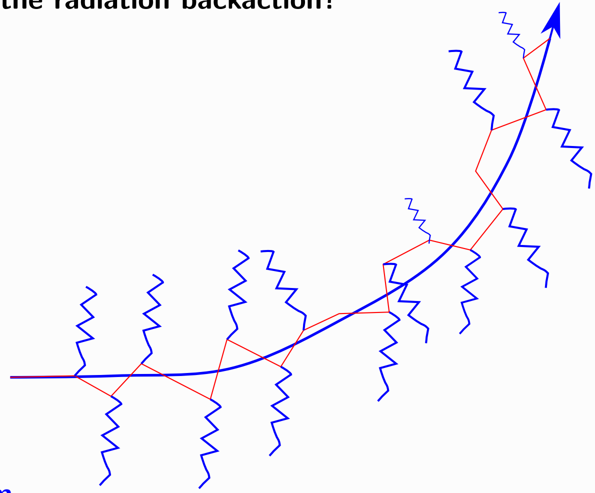
- $V_c = \Delta(p)/p_f \to 0$ for $p \to p_{node}$



- Radiation Dominated Dampling for $T \lesssim 0.1 T_c$

Radiation Damping - Pair-Breaking at $T \to 0$

Is their a transverse component of the radiation backaction?



Stochastic Radiative Dynamics

Fluctuations of the Chiral Vacuum

- Mesoscopic Ion coupled and driven through a Chiral “Bath”

Happy Birthday Tony!

Thanks for the beautiful physics you created and stimulated !