Electrons and ions on superfluid ^3He surface

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Acknowledgment

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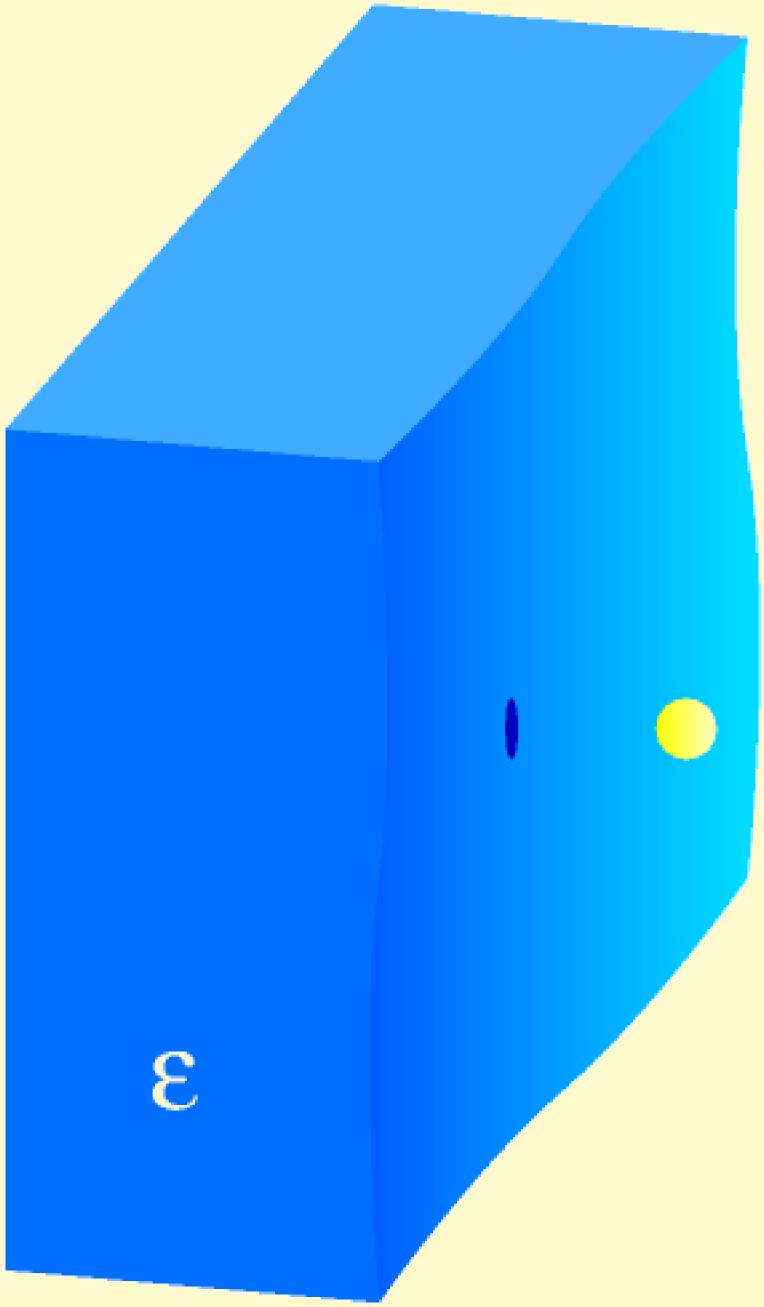
  - Yuriy Monarkha (Kharkov)

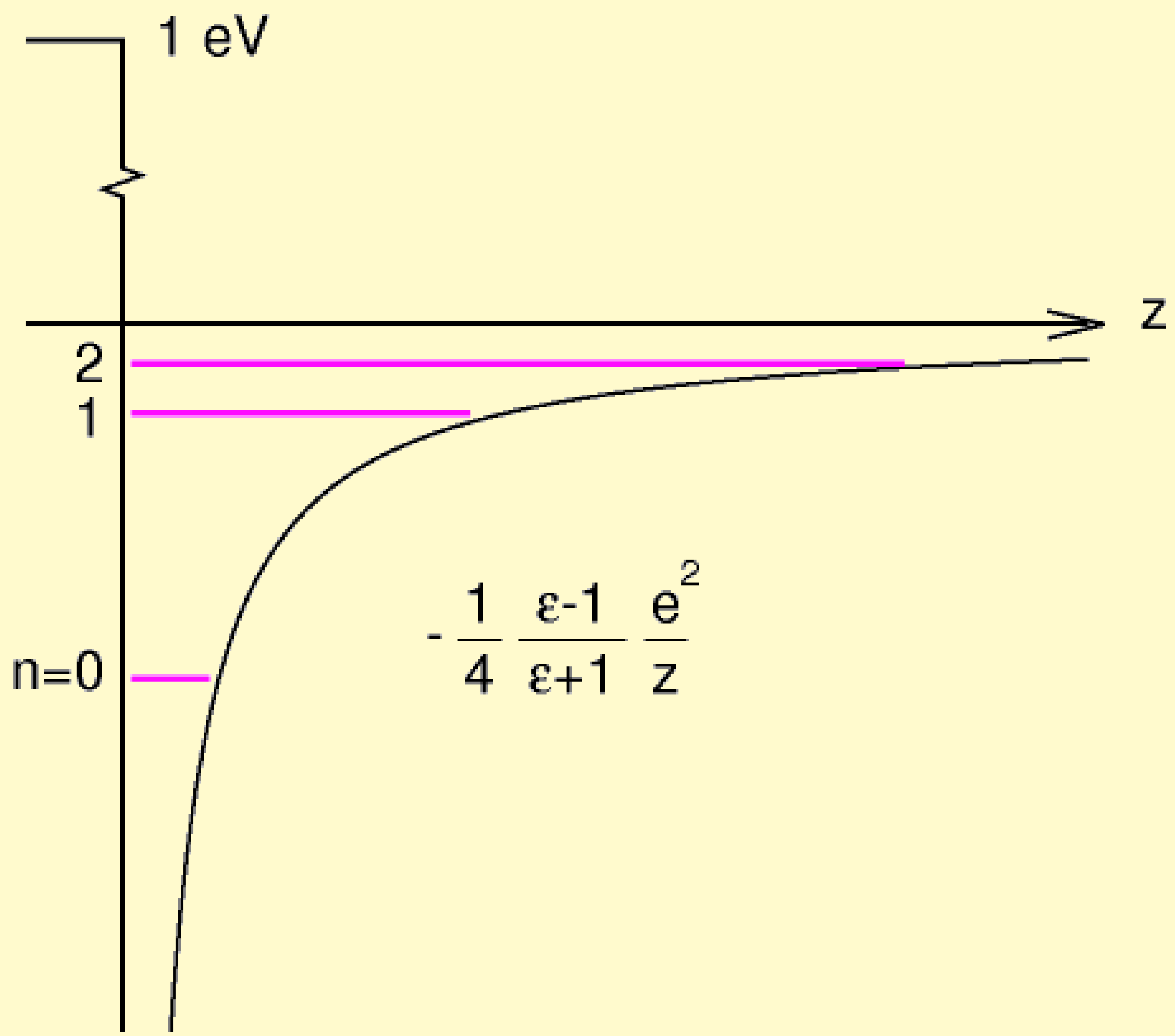
- Former collaborators:
  - K. Shiraham, H. Suto, T. Shiino, …

Outline

- Surface state electrons
- 2D Wigner solid (WS)
- Mobility measurment of WS on ^{3}He
- Quasiparticle scattering model
- Superfluid ^{3}He under magnetic fields
- Surface Texture
- Surface Bound States
- Mobility of Electron bubble
- Summary

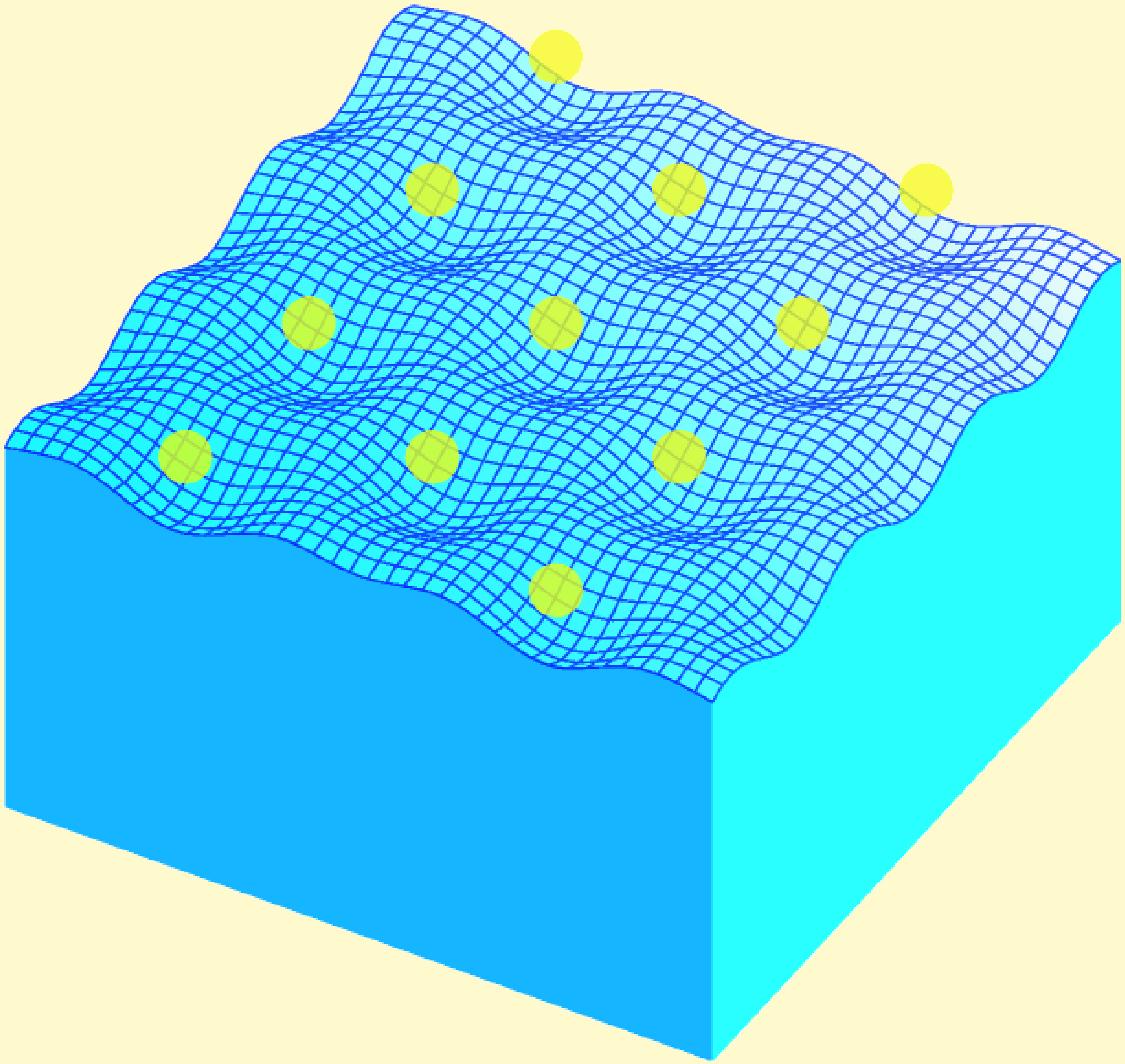
Surface state electrons



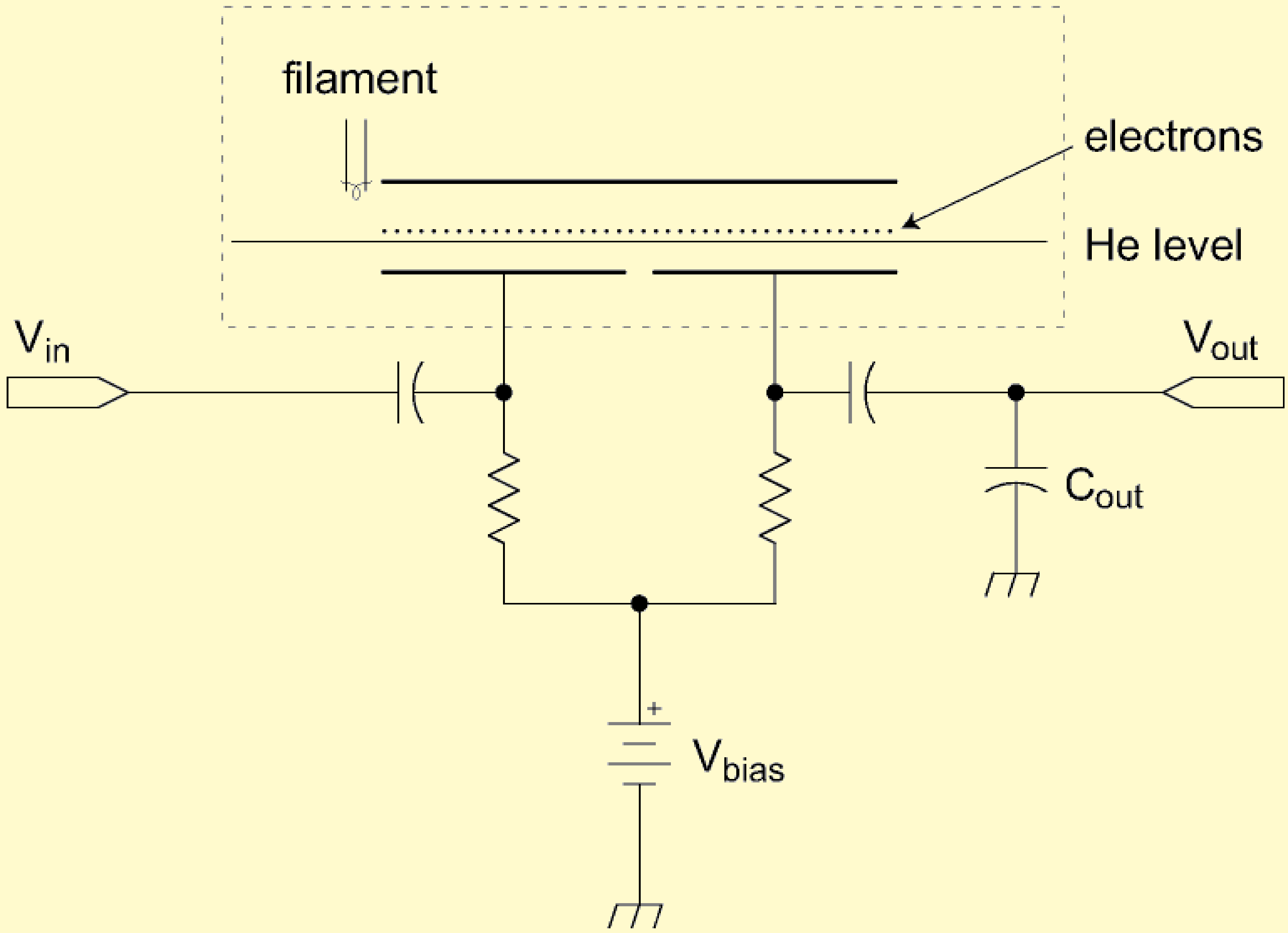


Wigner solid

C. C. Grimes and G. Adams: PRL 42 (1979) 795.
D. S. Fisher and B. I. Halperin, and P. M. Platzman: PRL 42 (1979) 798.

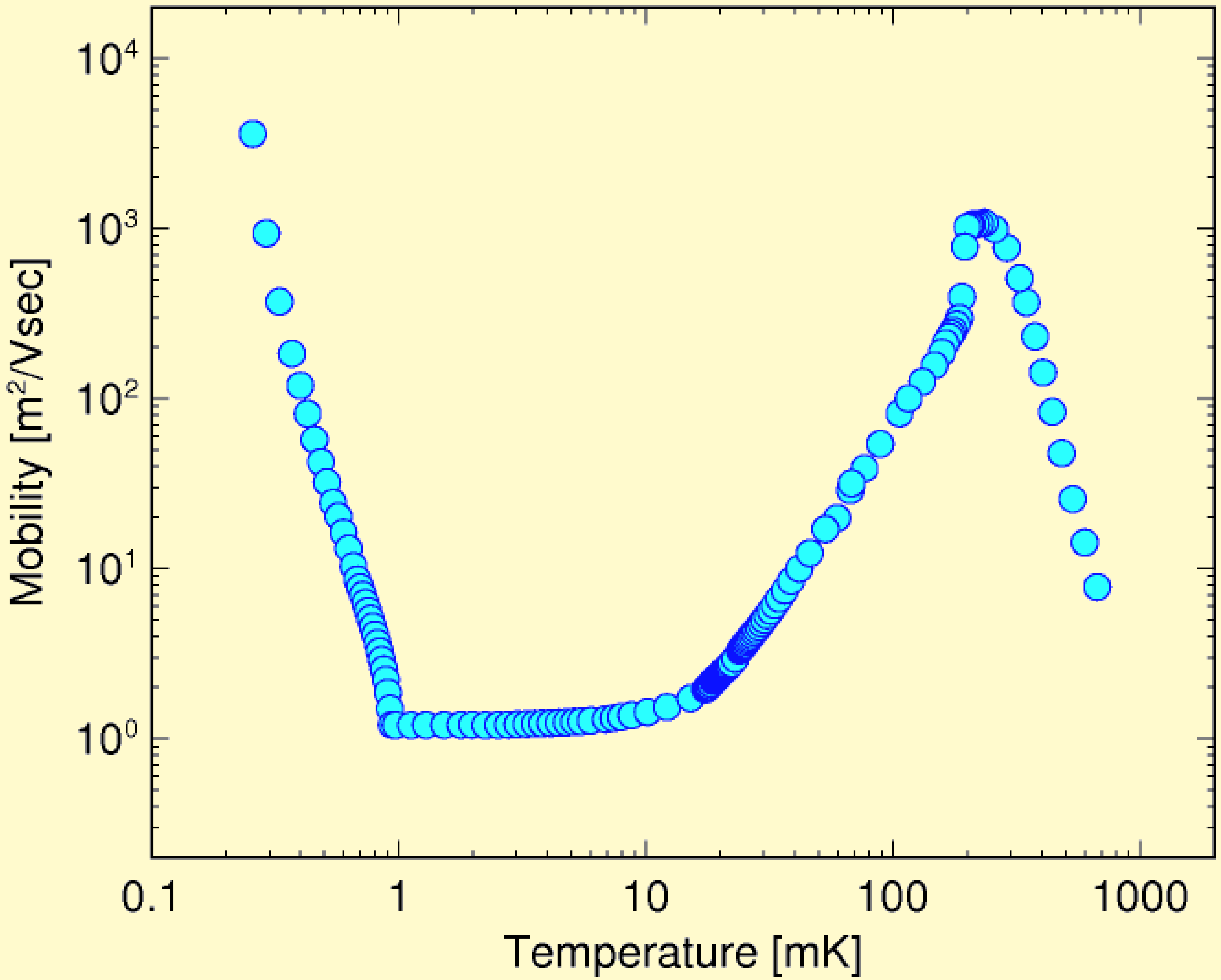


Setup



DC mobility

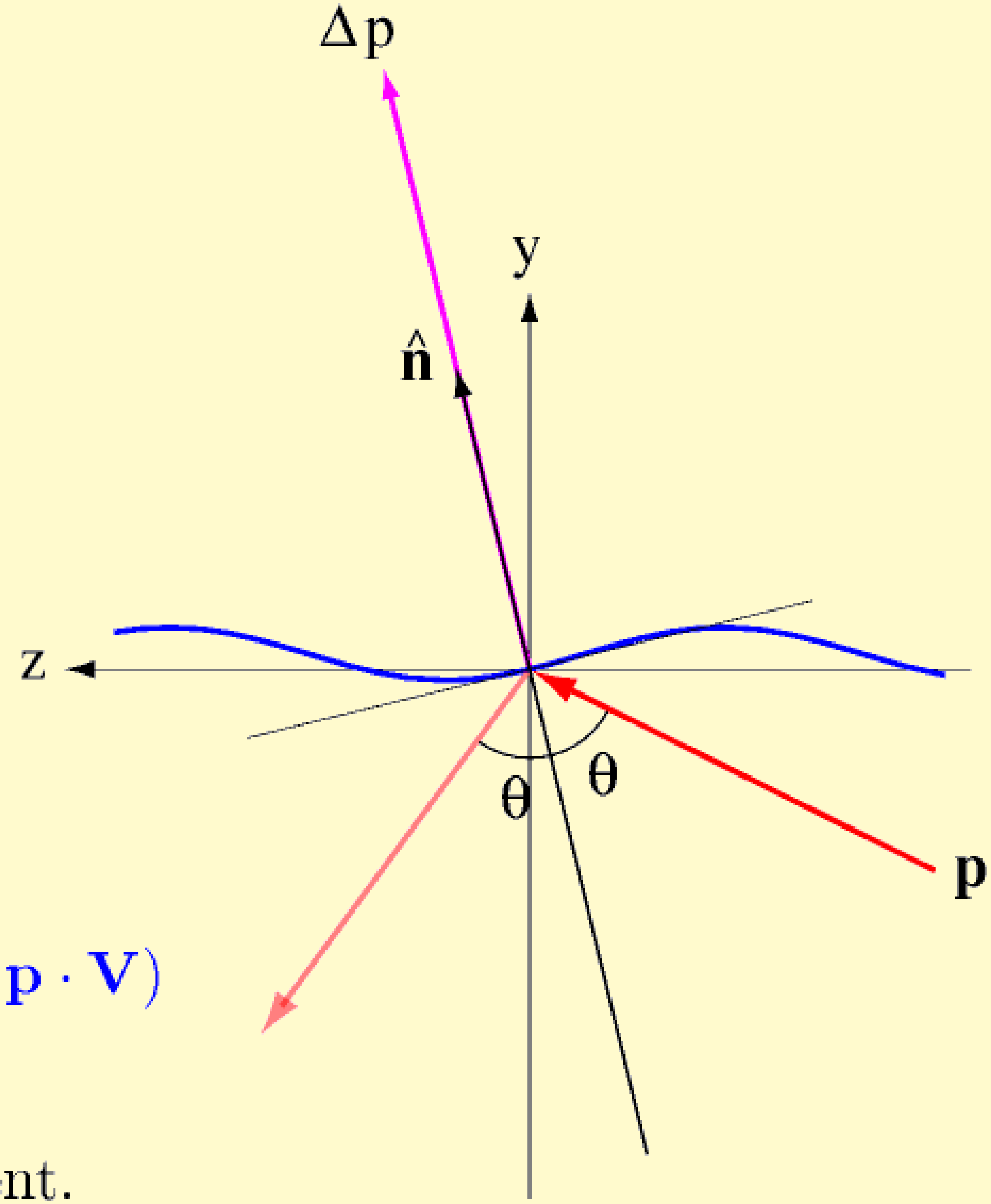
K. Shirahama, O. I. Kirichek, and K. Kono: PRL 79 (1997) 4218.
K. K., J. Low Temp. Phys. 126 (2002) 467.



Quasiparticle scattering (QPS) model

Yu. P. Monarkha and K. Kono: J. Phys. Soc. Jpn 66 (1997) 3901.
KK, H. Ikegami, and Yu. Monarkha: J. Phys. Soc. Jpn. 77 (2008) 111004.

- Kinetic theory of gas
- Low Temperature
- Ballistic
- Specular scattering



$$\Delta \mathbf{p} = 2(\hat{\mathbf{n}} \cdot \mathbf{p})\hat{\mathbf{n}}$$

$$\Phi_{\mathbf{p}} = (\hat{\mathbf{n}} \cdot \mathbf{v}) f(\varepsilon_{\mathbf{p}\sigma} - \mathbf{p} \cdot \mathbf{V})$$

$$\mathbf{F} = \int ds \sum_{\mathbf{p}\sigma}{}' 2\hat{\mathbf{n}}(\hat{\mathbf{n}} \cdot \mathbf{p})(\hat{\mathbf{n}} \cdot \mathbf{v}) f(\varepsilon_{\mathbf{p}\sigma} - \mathbf{p} \cdot \mathbf{V})$$

$\sum'$: 1/2 Fermi sphere. ds: Surface element.

Mobility expression

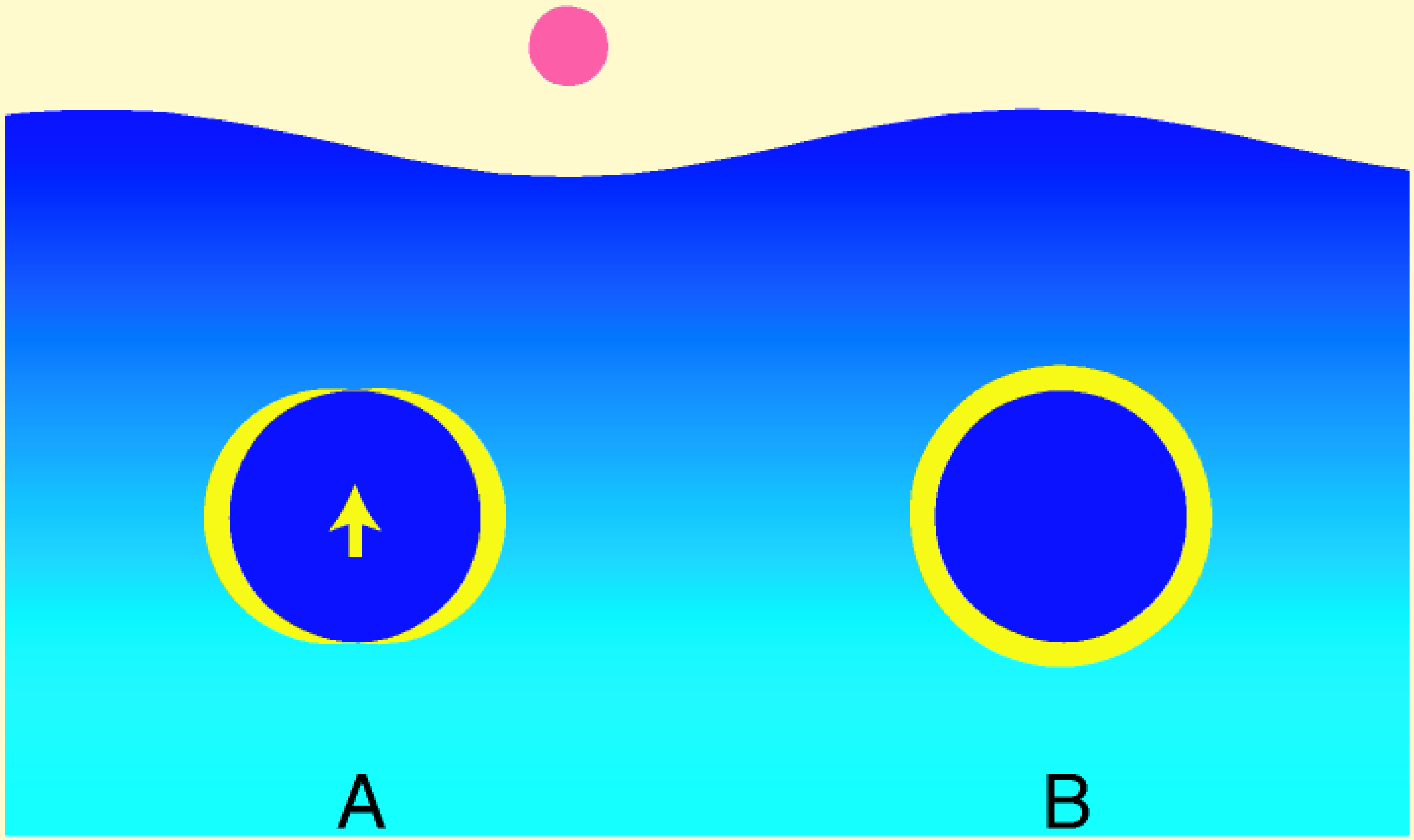
$$\frac{e}{\mu_{\rm n}} = \frac{p_{\rm F}^4}{4\pi^2\hbar^3 N_e}\int ds\, n_z^2$$

$$\frac{e}{\mu_{\rm s}} = \frac{8e}{\mu_{\rm n}}\left\langle \cos^3\theta\, f\left(E_{\mathbf{p}}(0)\right)\right\rangle' , \quad E_{\mathbf{p}}(\xi_p) = \sqrt{\xi_p^2+\Delta^2}$$

$$\to \frac{2e}{\mu_{\rm n}}\frac{1}{\exp\left(\frac{\Delta_{\rm B}(T)}{T}\right)+1} \quad \text{for the B phase.}$$

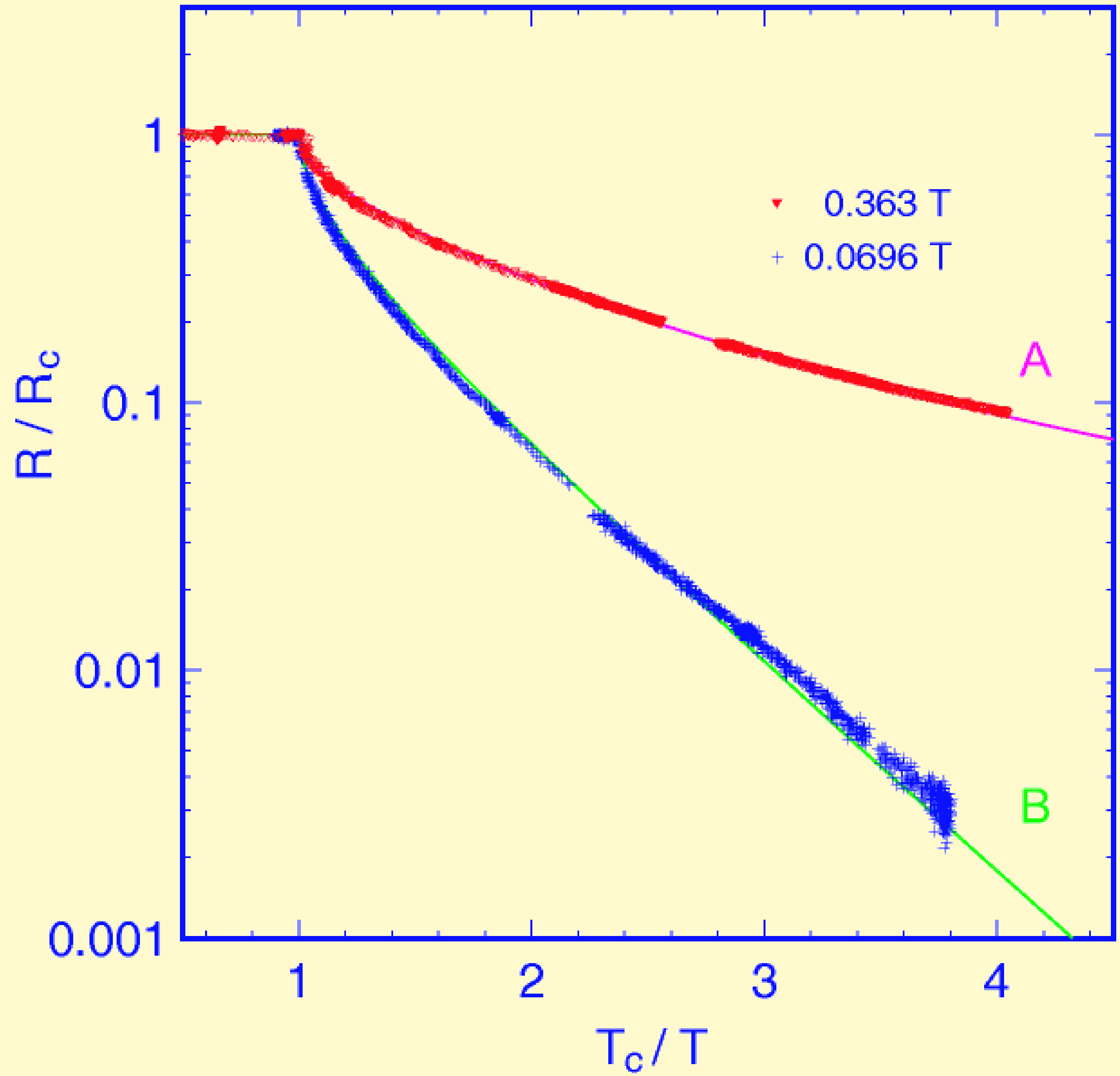
$$\to \frac{8e}{\mu_{\rm n}}\left\langle \frac{\cos^3\theta}{\exp\left(\frac{\Delta_{\rm A}(T)\sin\theta}{T}\right)+1}\right\rangle' \quad \text{for the A phase}$$

Energy gaps

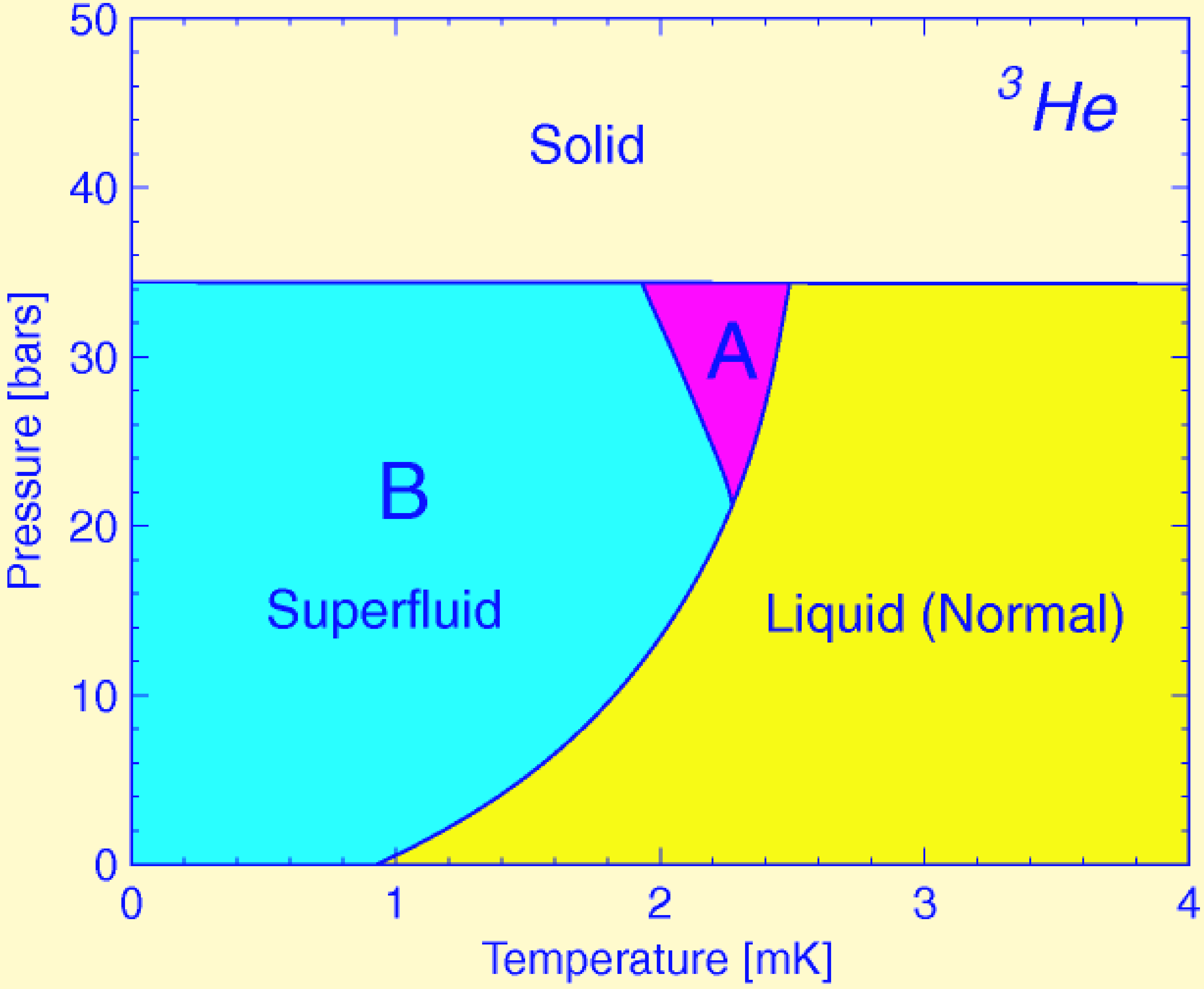


$\hat{\boldsymbol{l}}$ vector

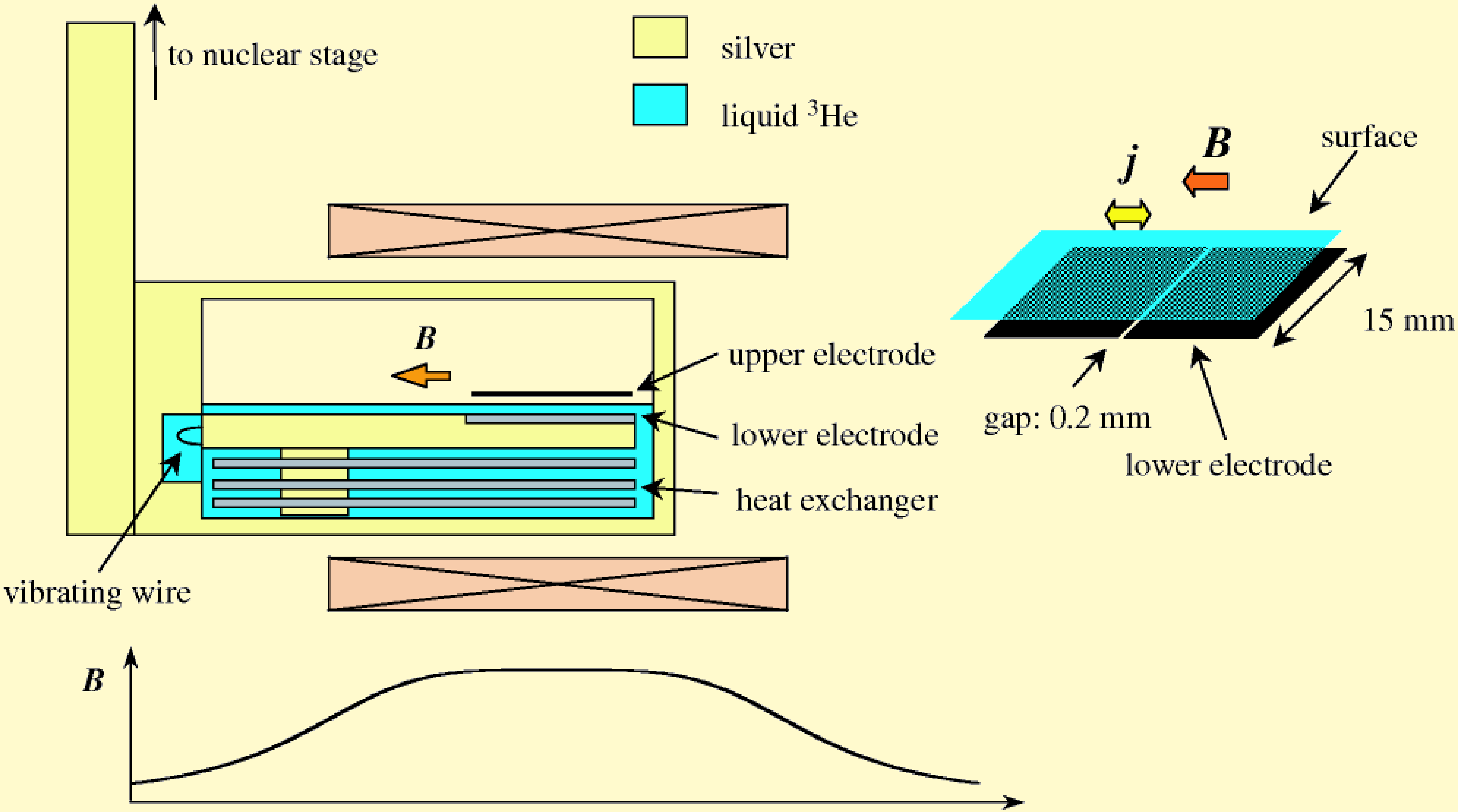
Comparison with experiment



Phase diagram of He-3

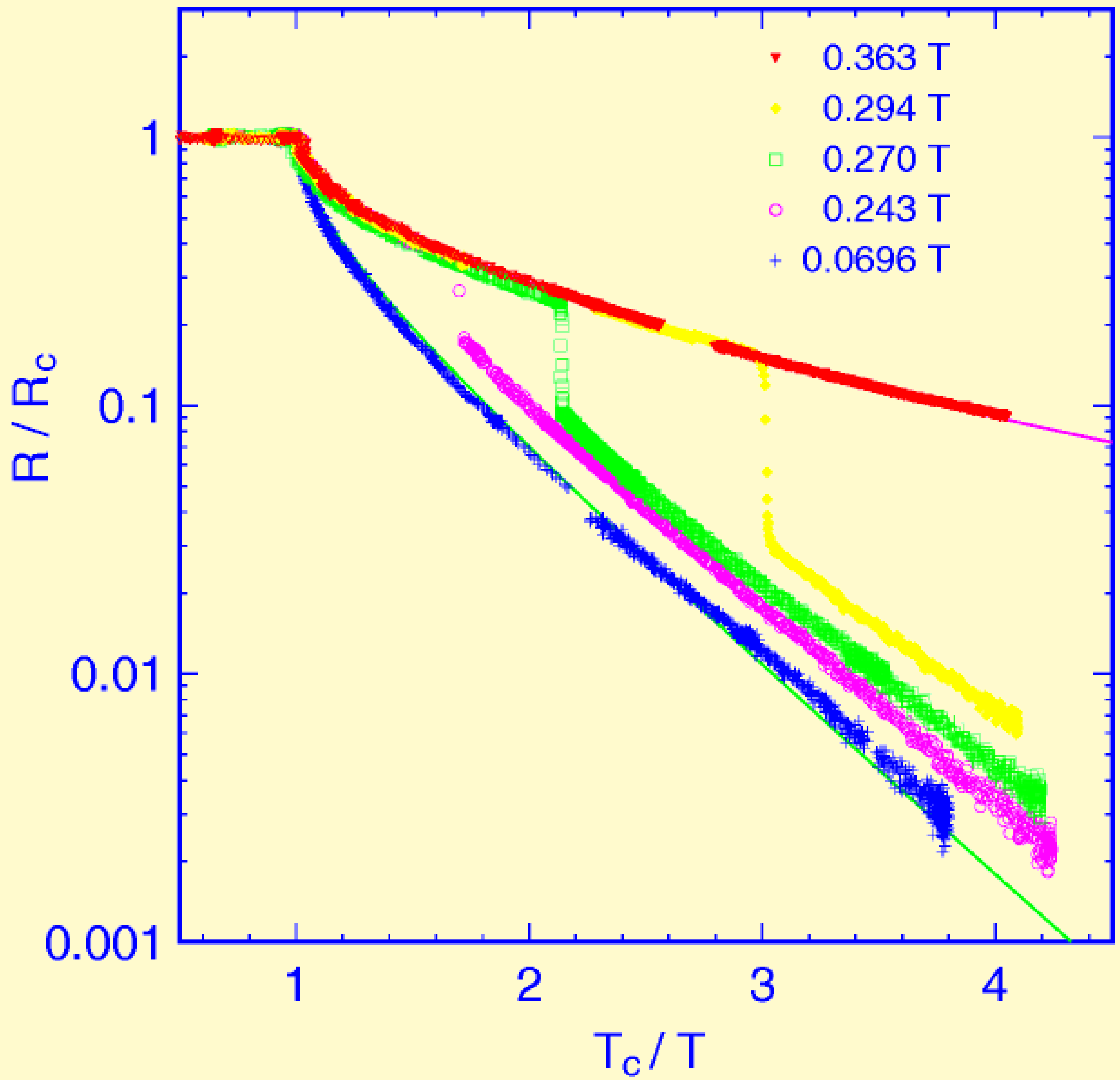


To create A-phase

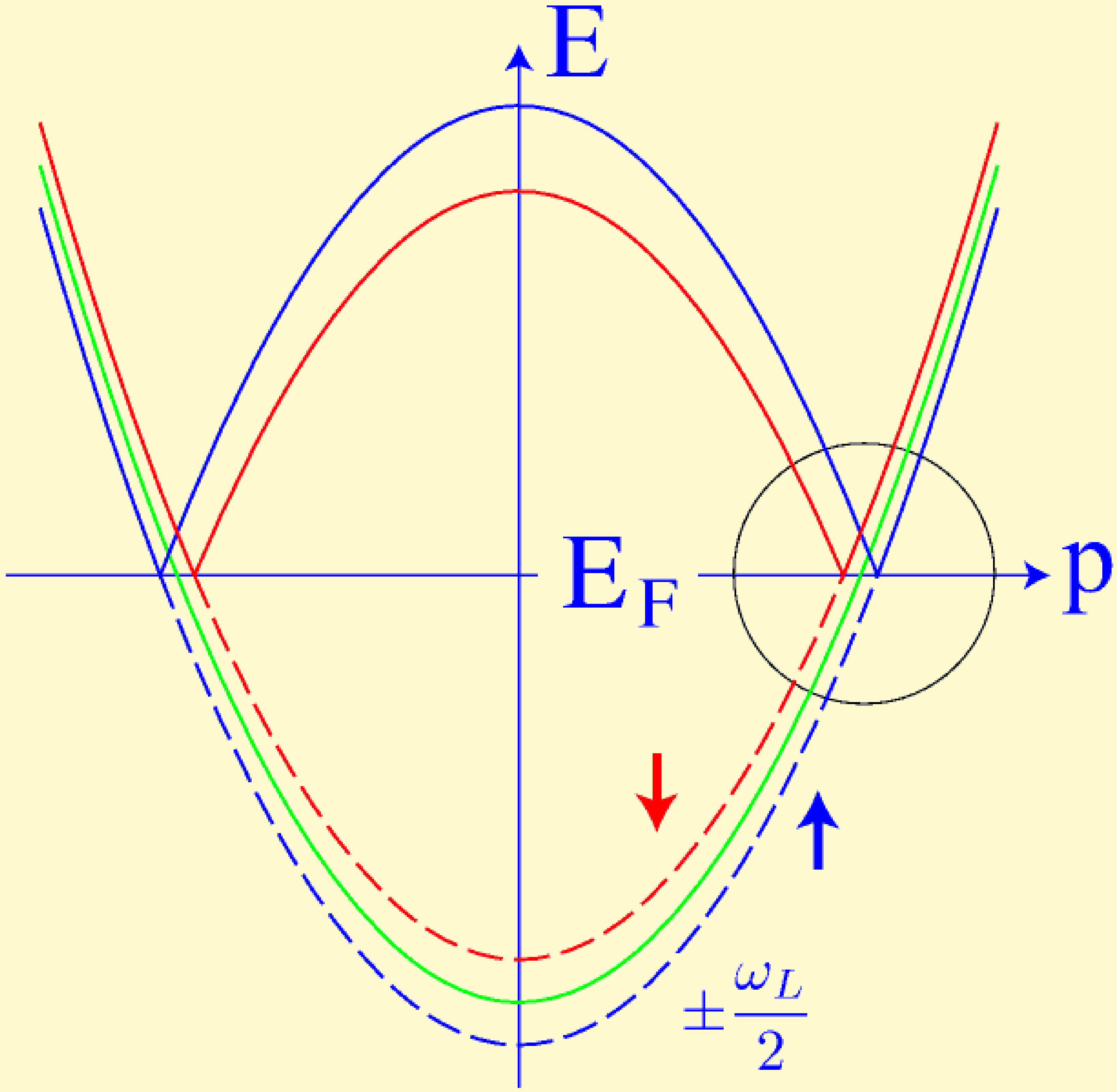


Experimental observation

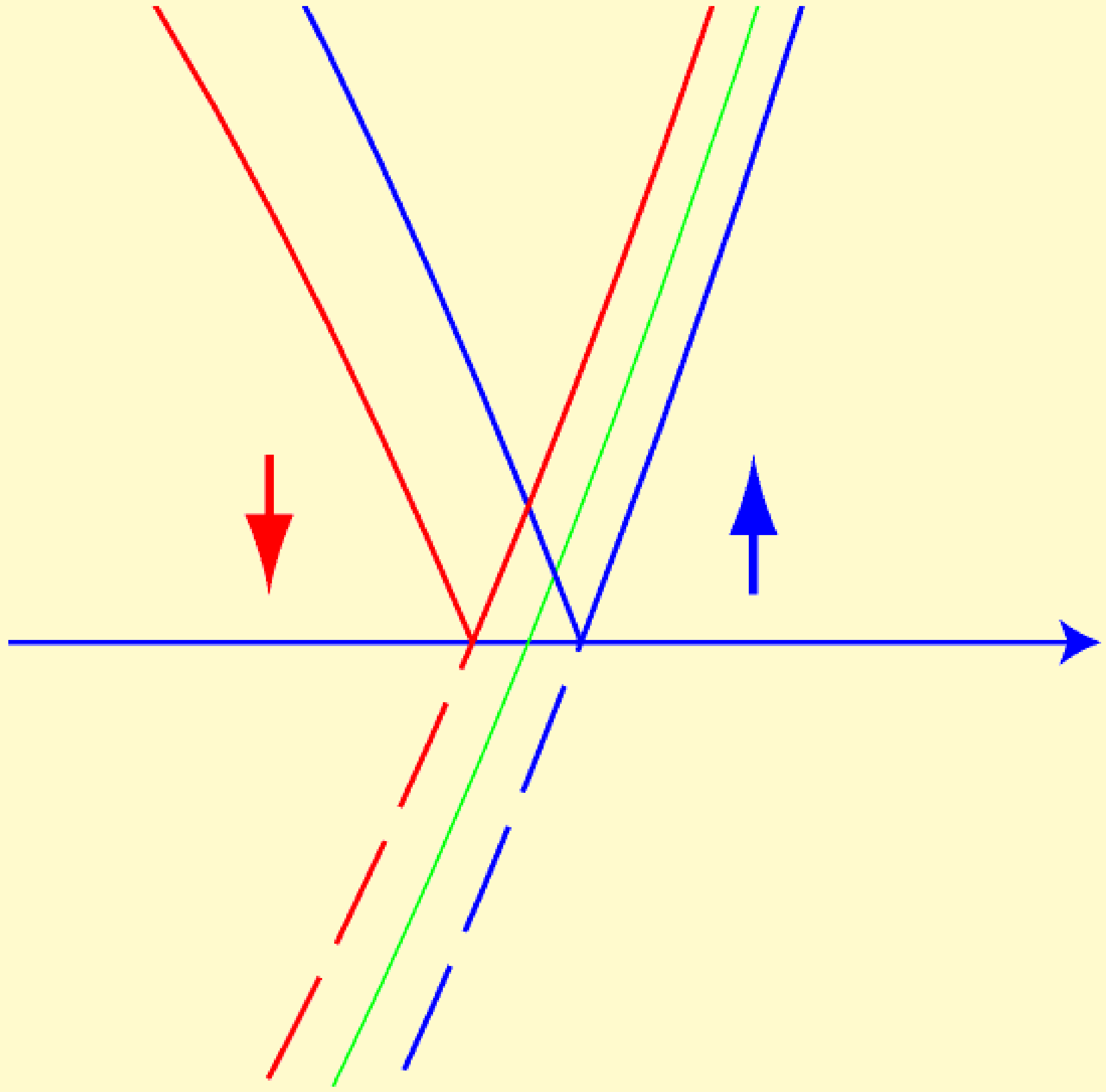
H. Ikegami and K. Kono: PRL 97 (2006) 165303



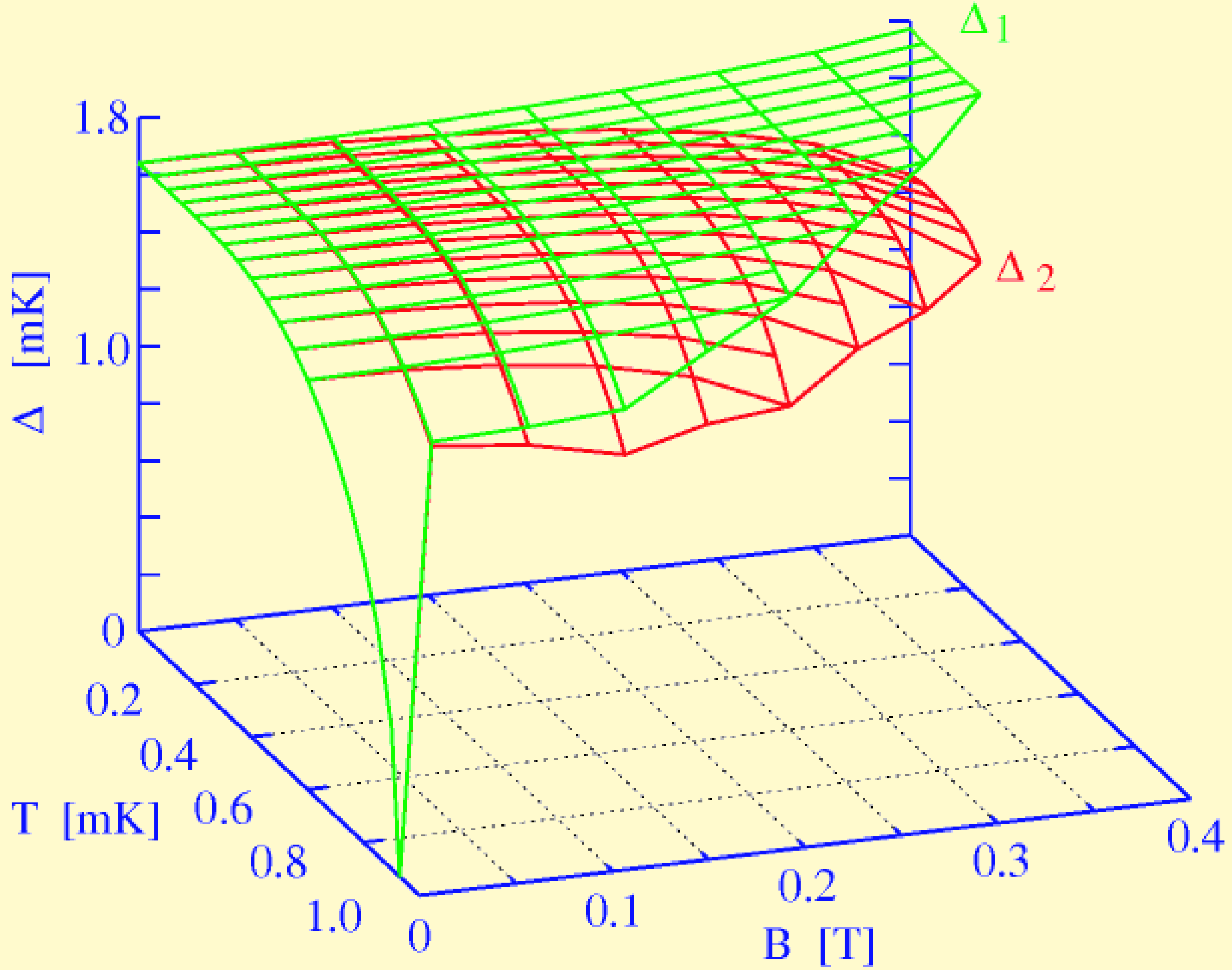
Magnetic field (Zeeman effect)



Zeeman effect 2

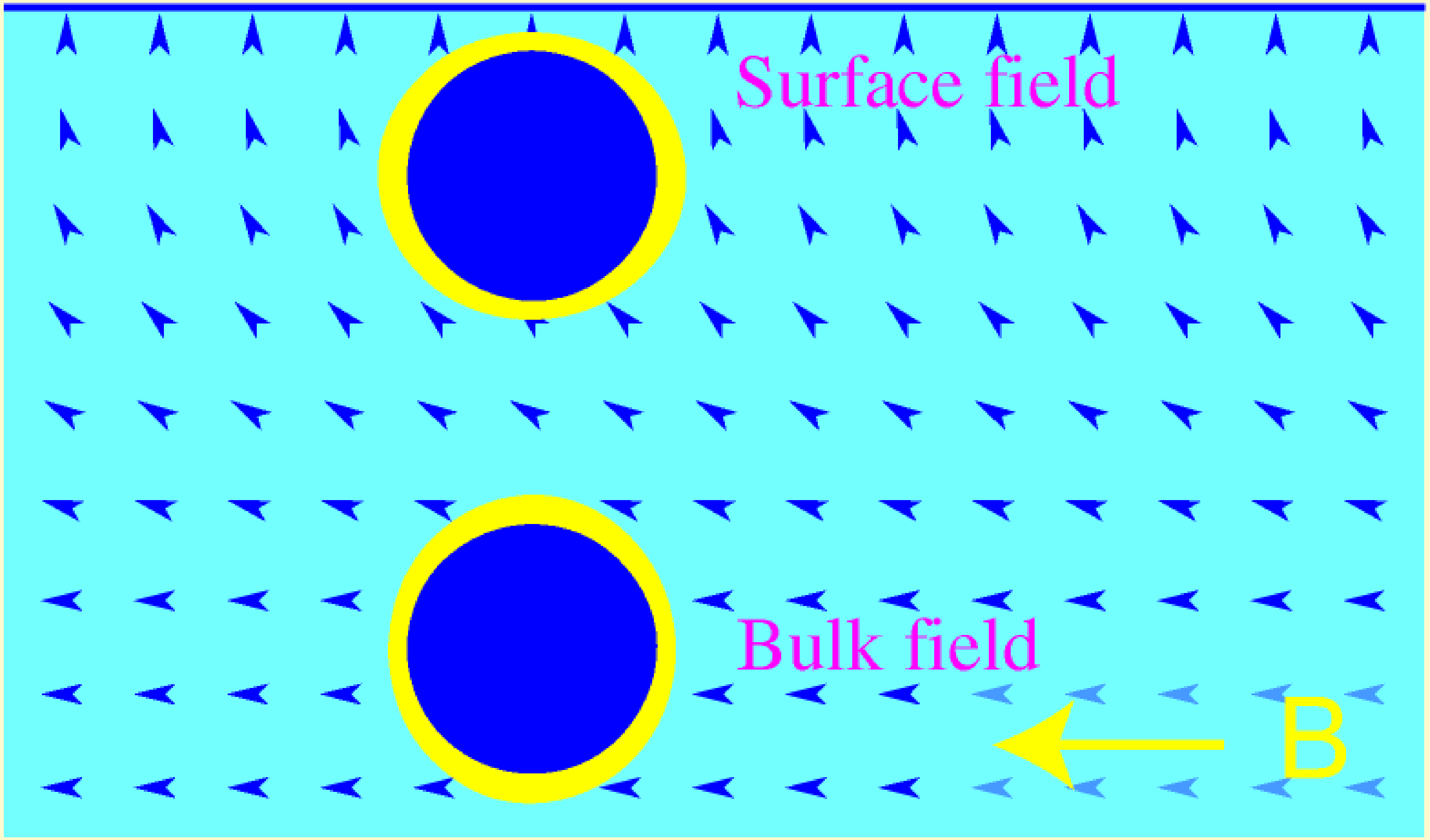


Energy gap in B

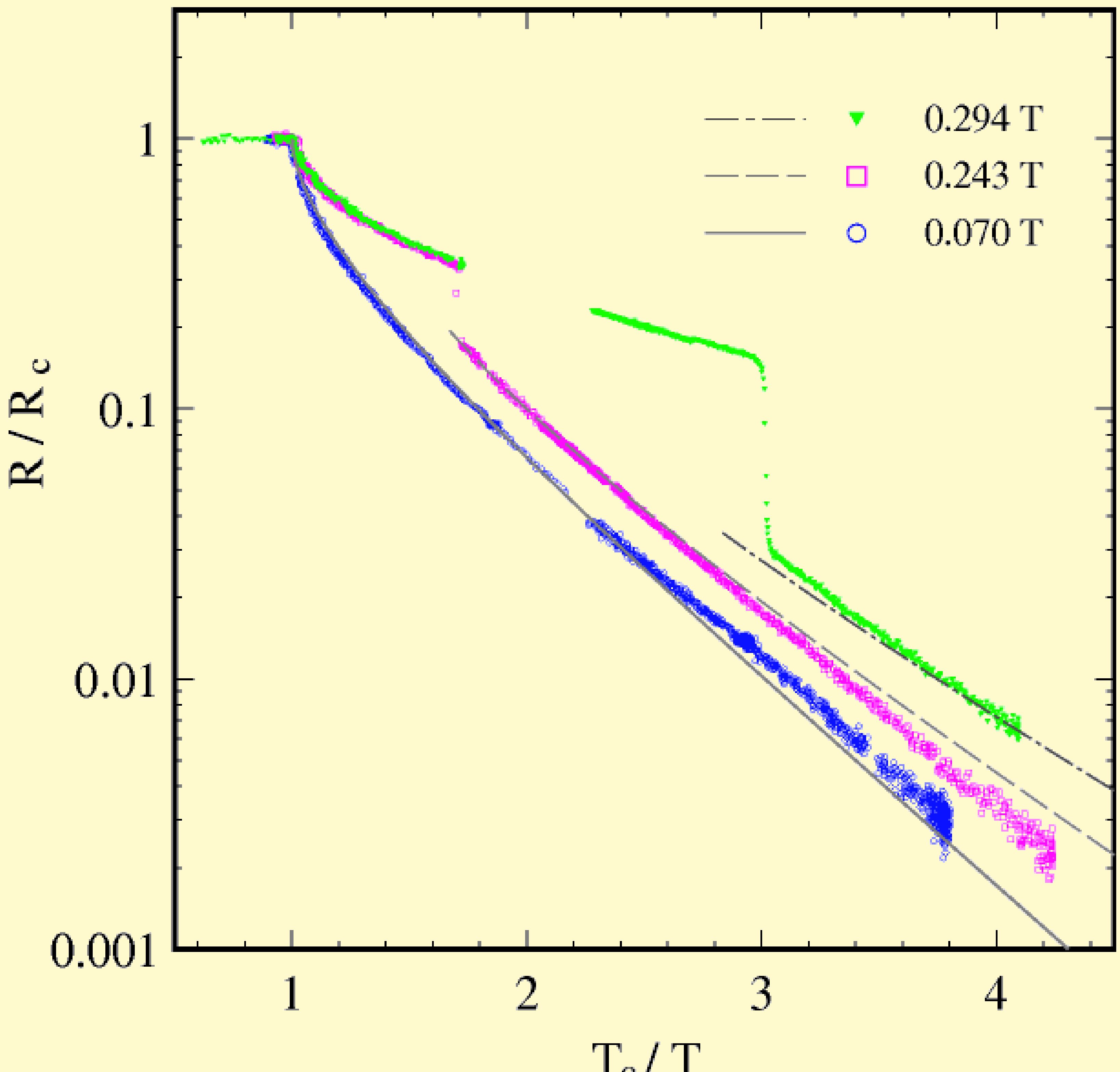


B phase texture

W. F. Brinkman, H. Smith, D. D. Osheroff, and E. I. Blount: PRL 33 (1974) 624.

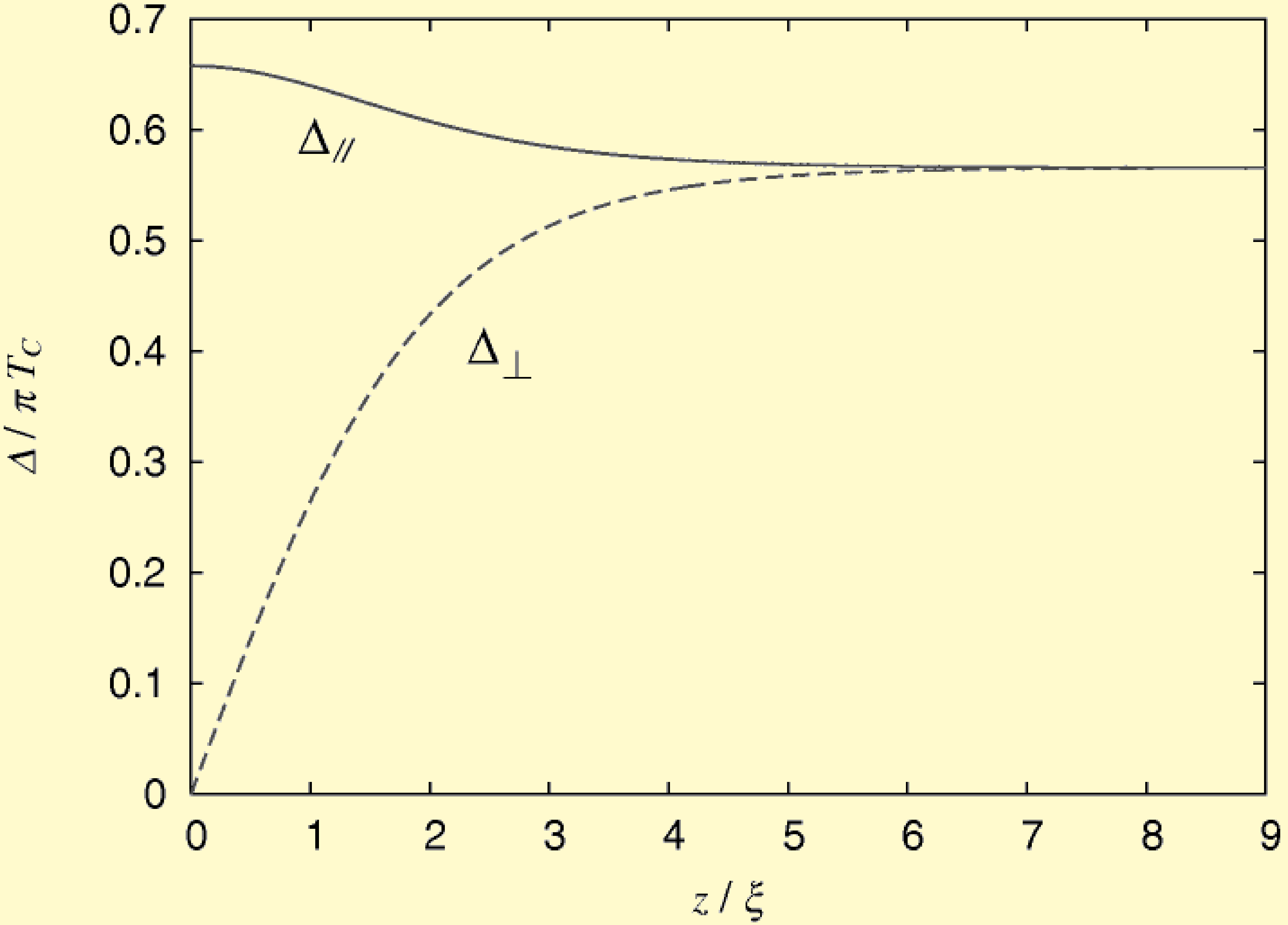


Magnetic filed dependence

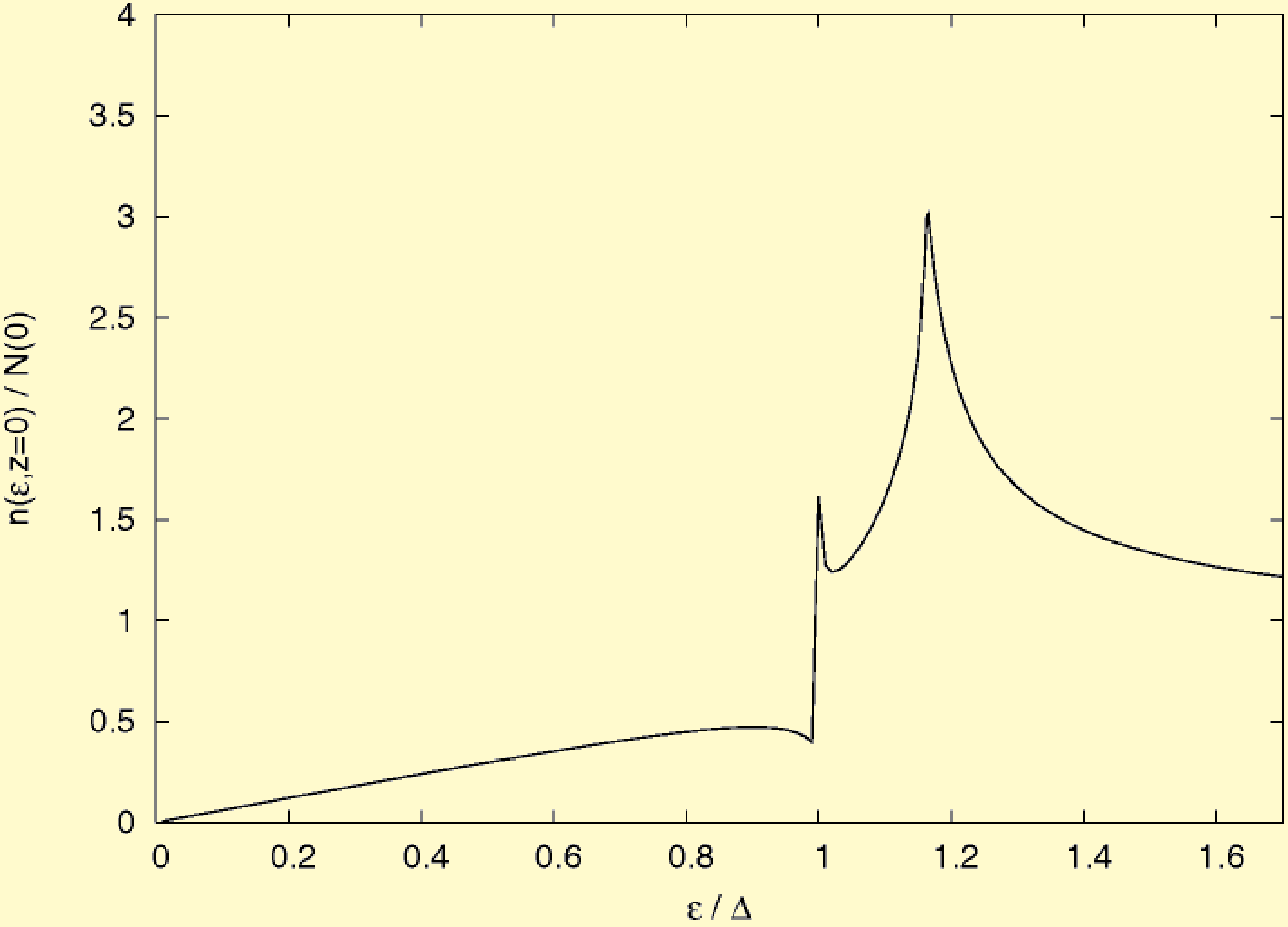


Order parameter at surface

Katsuhiko Nagai et al.: J. Phys. Soc. Jpn., 77 (2008) 111003
"Surface Bound States in Superfluid 3He"

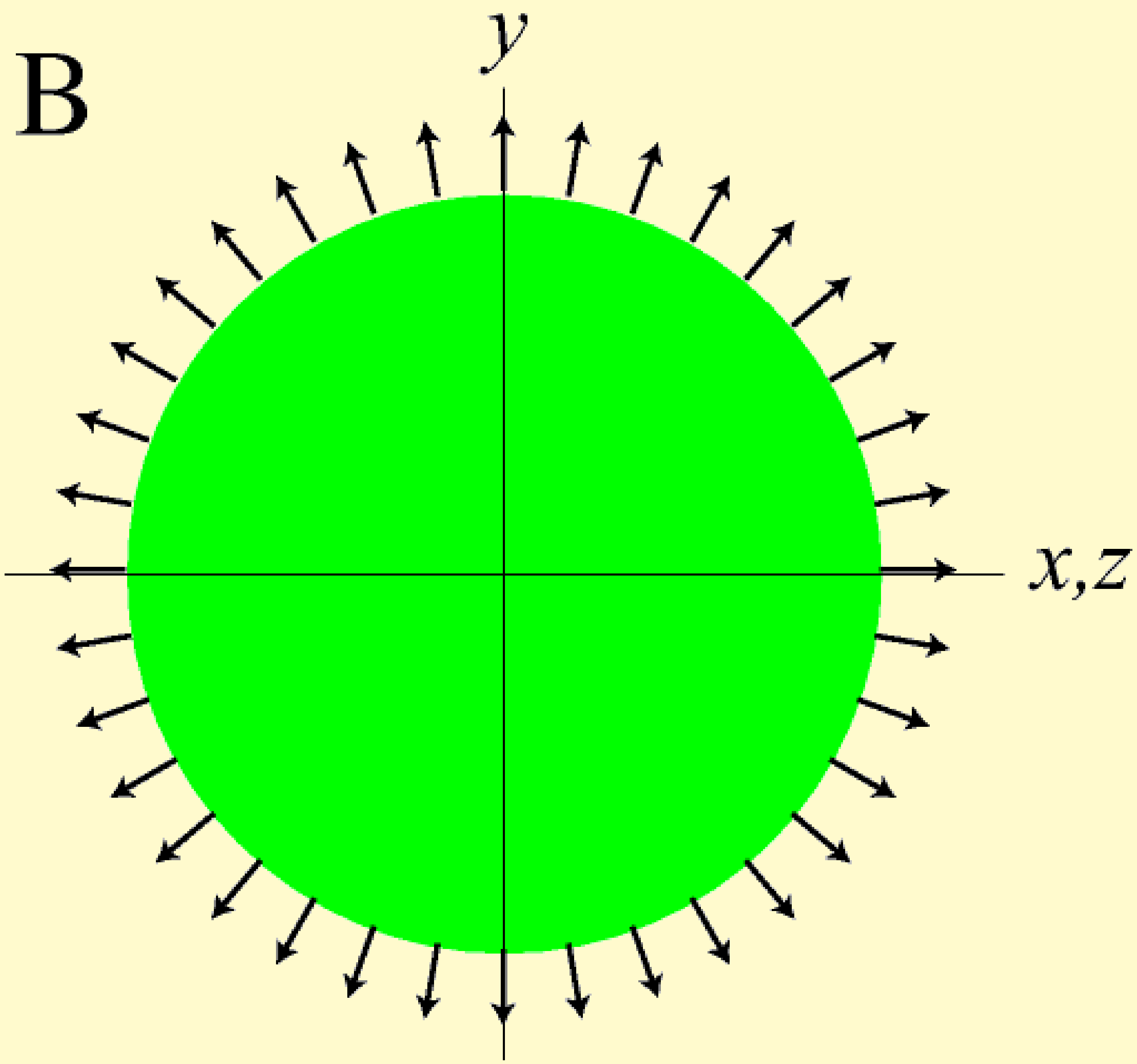


Surface density of states



Aoki et al.: Phys. Rev. Lett. 95 (2005) 075301

Order parameter



Majorana particle surface state

S. B. Chung and S. C. Zhang: PRL 103, 235301 (2009)
"Detecting the Majorana Fermion Surface State 0f 3He-B
through Spin Relaxation"

$$(z < 0)$$

$$\begin{pmatrix} \hat{\psi}_{\rightarrow}(\mathbf{r}) \\ \hat{\psi}_{\leftarrow}(\mathbf{r}) \\ \hat{\psi}^{\dagger}_{\rightarrow}(\mathbf{r}) \\ \hat{\psi}^{\dagger}_{\leftarrow}(\mathbf{r}) \end{pmatrix} = \sum_{\mathbf{k}} (\hat{\gamma}_{\mathbf{k}} e^{i\mathbf{k}_{\parallel}\cdot\mathbf{r}_{\parallel}} + \hat{\gamma}^{\dagger}_{\mathbf{k}} e^{-i\mathbf{k}_{\parallel}\cdot\mathbf{r}_{\parallel}}) \begin{pmatrix} \cos\frac{\phi_{\mathrm{k}}+\pi/2}{2} \\ \sin\frac{\phi_{\mathrm{k}}+\pi/2}{2} \\ \cos\frac{\phi_{\mathrm{k}}+\pi/2}{2} \\ \sin\frac{\phi_{\mathrm{k}}+\pi/2}{2} \end{pmatrix} u_{\mathbf{k}} e^{z/\xi} \sin(k_{\perp} z)$$

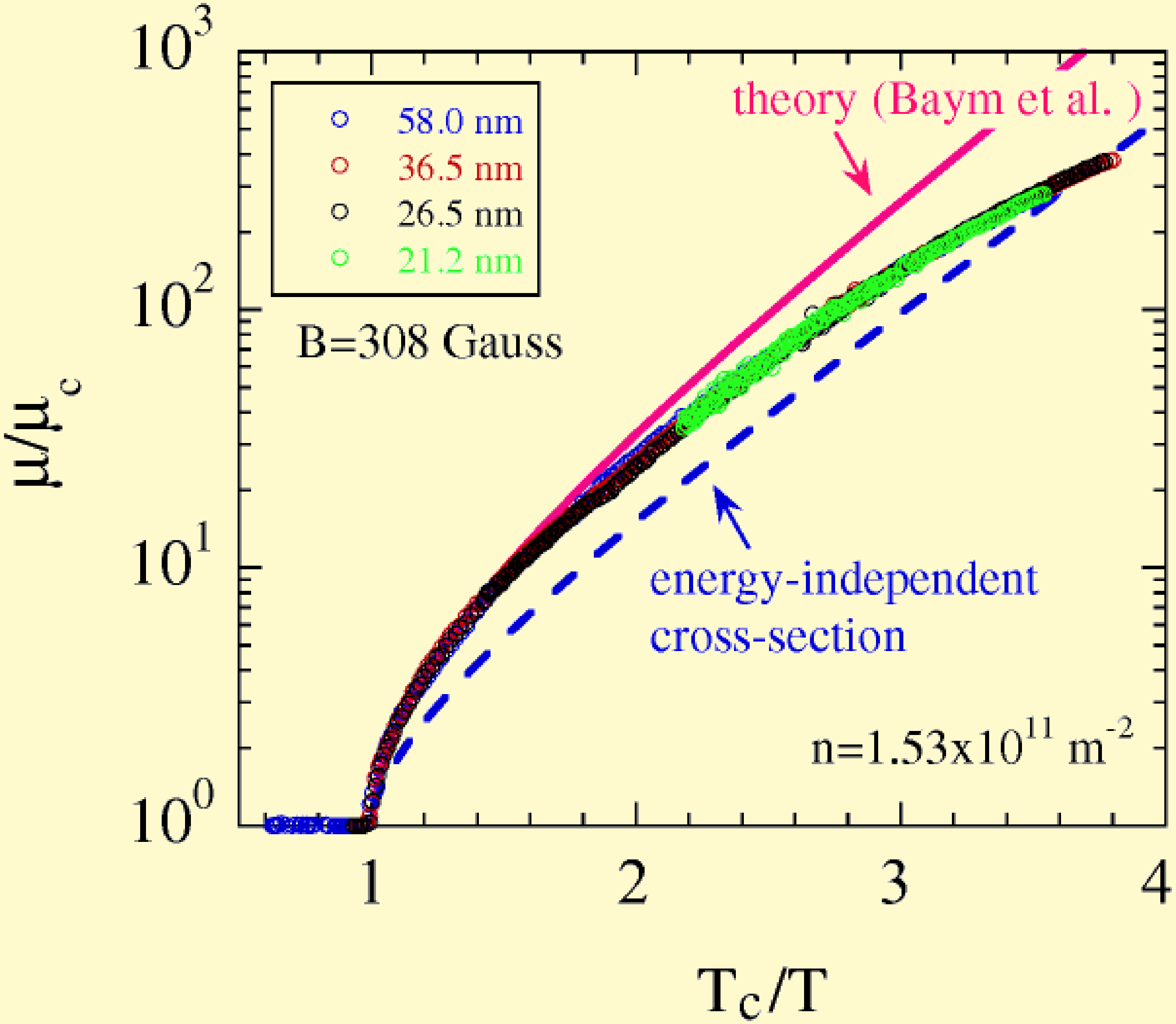
$$\phi_{\mathbf{k}} = \arctan\left(\frac{k_y}{k_x}\right), \quad u_{\mathbf{k}}:\ \text{normalization constant}$$

$$\hat{\psi}_{\rightarrow}(\mathbf{r}) = \hat{\psi}^{\dagger}_{\rightarrow}(\mathbf{r}) \quad \text{(Majorana)}$$

$$\rho(\mathbf{r}) = \sum_{\sigma} \hat{\psi}^{\dagger}_{\sigma}(\mathbf{r}) \hat{\psi}_{\sigma}(\mathbf{r}) \equiv 0$$

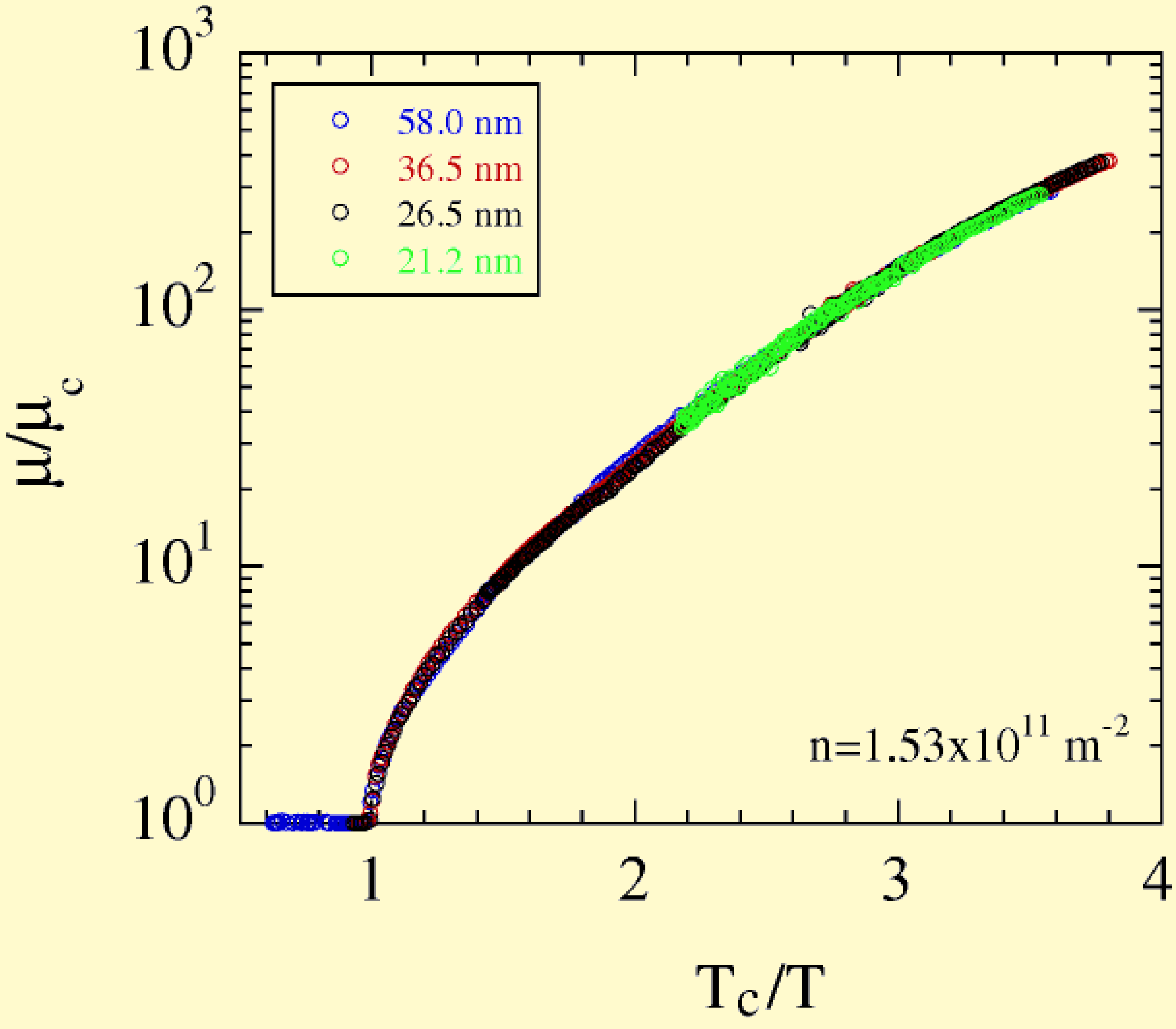
Ion mobility (experiment)

cf. T. Shiino et al.: J. Low Temp. Phys. 126 (2002) 493.



Theory of electron bubble should be revisited!

No depth dependence!



No scattering by Majorana surface states?

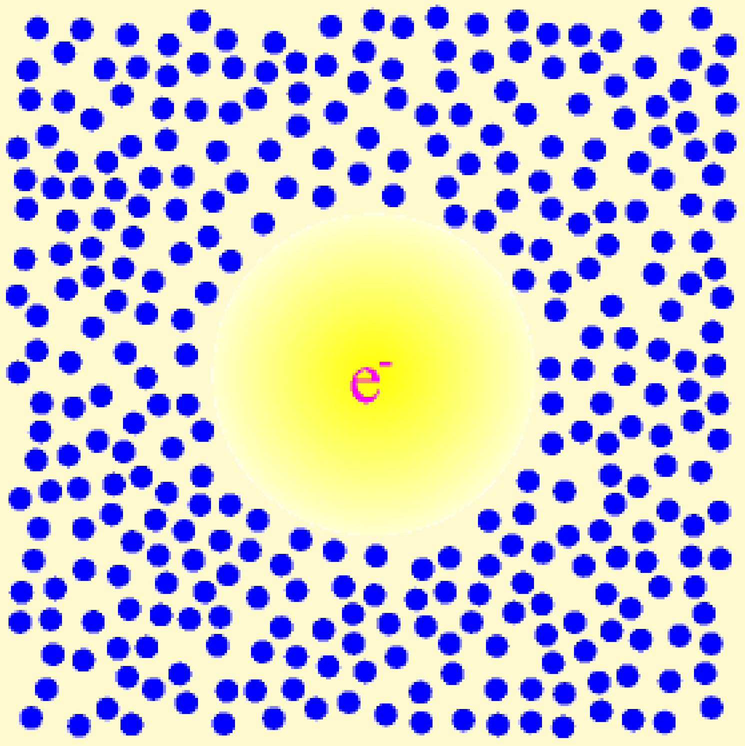
G. Baym et al.: J. Low Temp Phys. 36 (1979) 431.

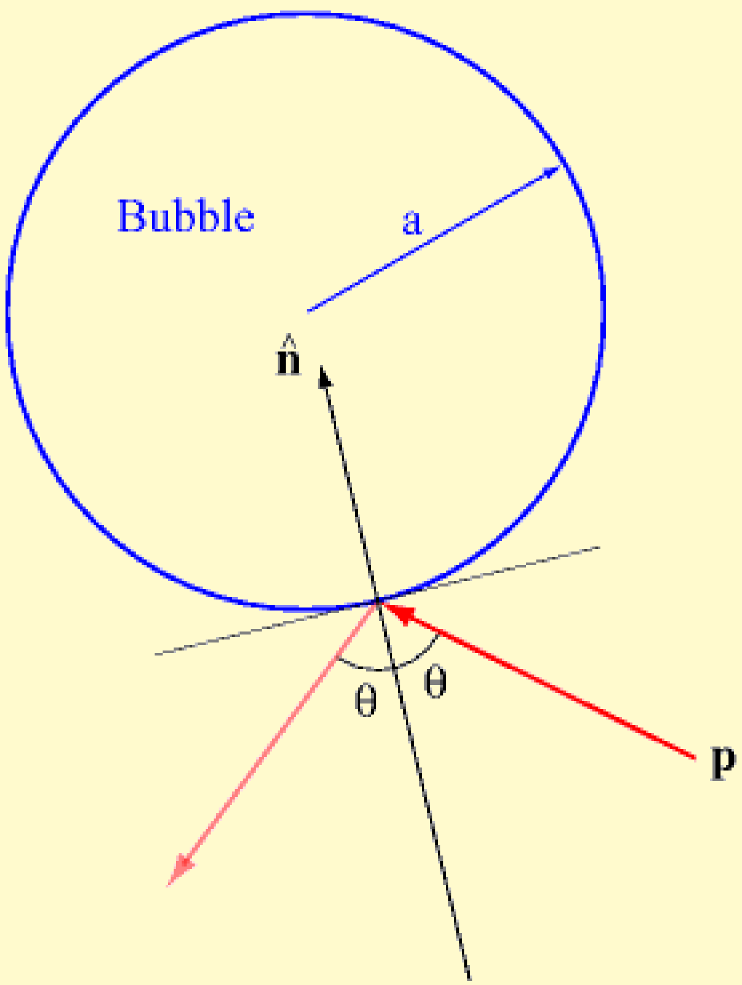
Then the rate at which an ion drifting with velocity **v** transfers momentum to the ^{3}He via "exchange" of density fluctuations of momentum **k** and energy ω from the ion to the ^{3}He is (in unit volume)

$$\frac{d\mathbf{P}}{dt} = n_3 \sum_{\mathbf{k}} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \mathbf{k} S_3(\mathbf{k}, \omega) S_i(-\mathbf{k}, -\omega, \mathbf{v}) |t(\mathbf{k}, \omega, \mathbf{v})|^2 \tag{1}$$

Here n_3 is the ^{3}He particle density, $S_3(\mathbf{k}, \omega)$ is the equilibrium structure function for ^{3}He density fluctuations, and $S_i(-\mathbf{k}, -\omega, \mathbf{v})$ similarly describes the spectrum of possible energy transfers $-\omega$ to the drifting ion, for a given momentum transfer $-\mathbf{k}$. We assume at this point that t, the matrix element for this scattering process, depends only on $\mathbf{k}$, ω, and $\mathbf{v}$.

Quasiparticle scattering by bubble





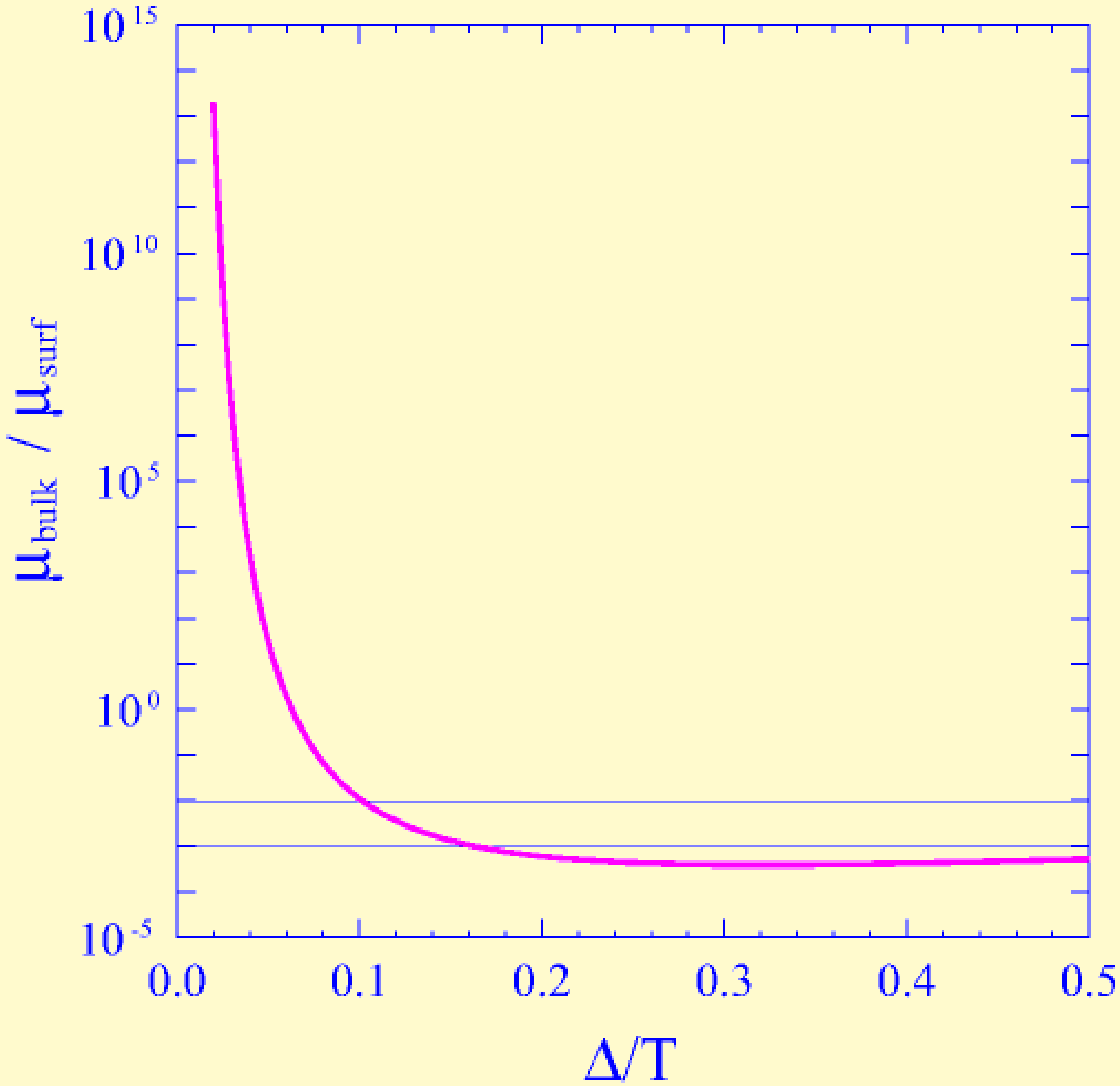
$$\frac{e}{\mu} = \frac{2}{3} p_{\rm F}^2 v_{\rm F} N(0) \pi a^2 = n_3 p_{\rm F} \pi a^2$$

$$\frac{e}{\mu} = n_3 p_{\rm F} \sigma_{tr}^N, \quad \sigma_{tr}^N = \pi a^2$$

G. Baym, C.J. Pethick, and M. Salomaa: Phys. Rev. Lett. 38 (1977) 845.

Surface state contribution

$$\frac{\mu_{bulk}}{\mu_{surf}} \approx \frac{1}{k_{\mathrm{F}}\xi}\left(\frac{T}{\Delta}\right)^3 \frac{(e^{\Delta/T}+1)}{2}, \quad \frac{1}{k_{\mathrm{F}}\xi} \sim 10^{-3}$$



Summary

- Wigner Solid as a probe of liquid He surface
- Quasiparticle scattering model
- Anisotropy in superfluid ^{3}He.
- Ion pool as a probe of liquid He surface
- Surface bound states?