Transverse Acoustic Response of Superfluid ^3He at High Magnetic field

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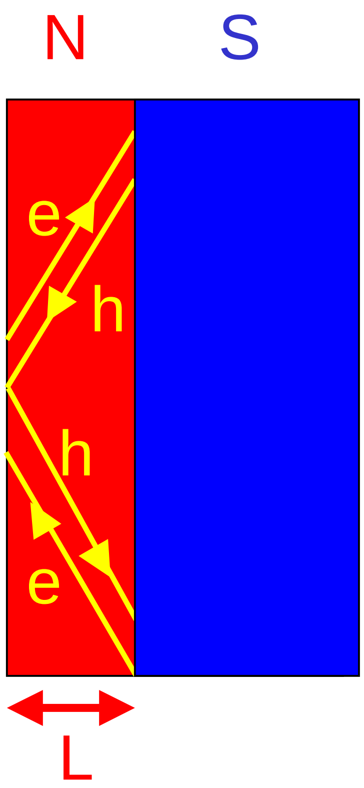
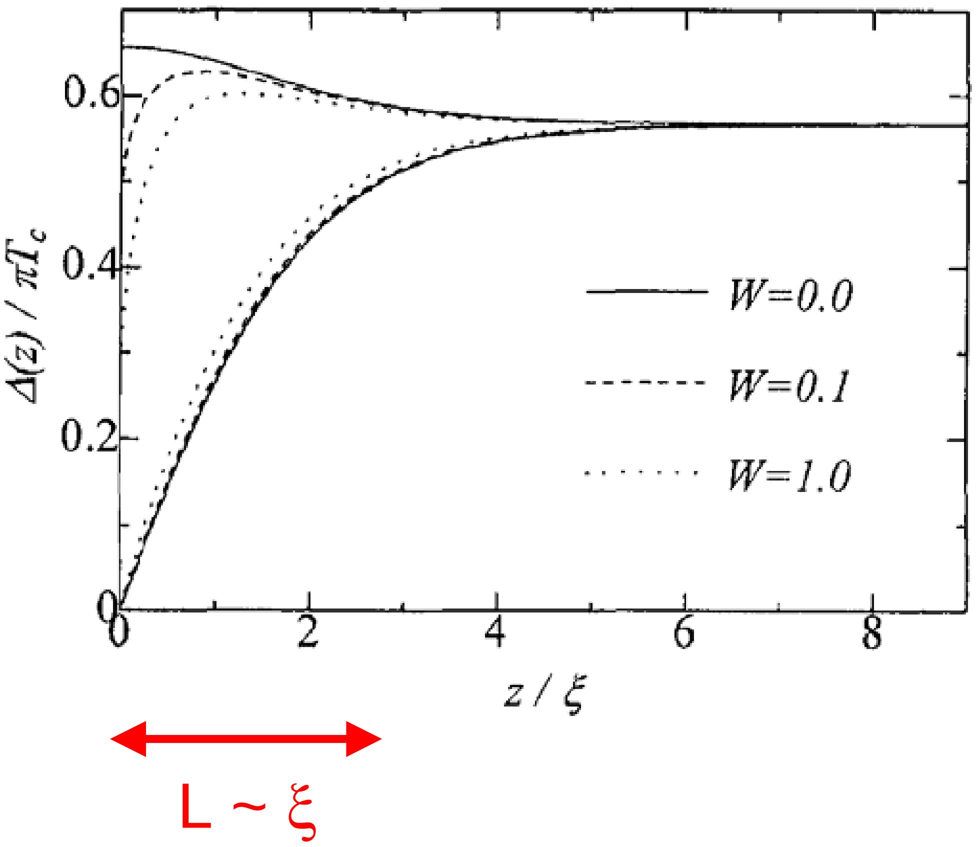
1. Introduction, Surface Andreev Bound States.
2. Review on SABS in B phase.
3. Superfluidity of 4He films pressurized by 3He.
4. Acoustic response of superfluid 3He at high magnetic field.

Andreev Saint-James Bound States (ABS)

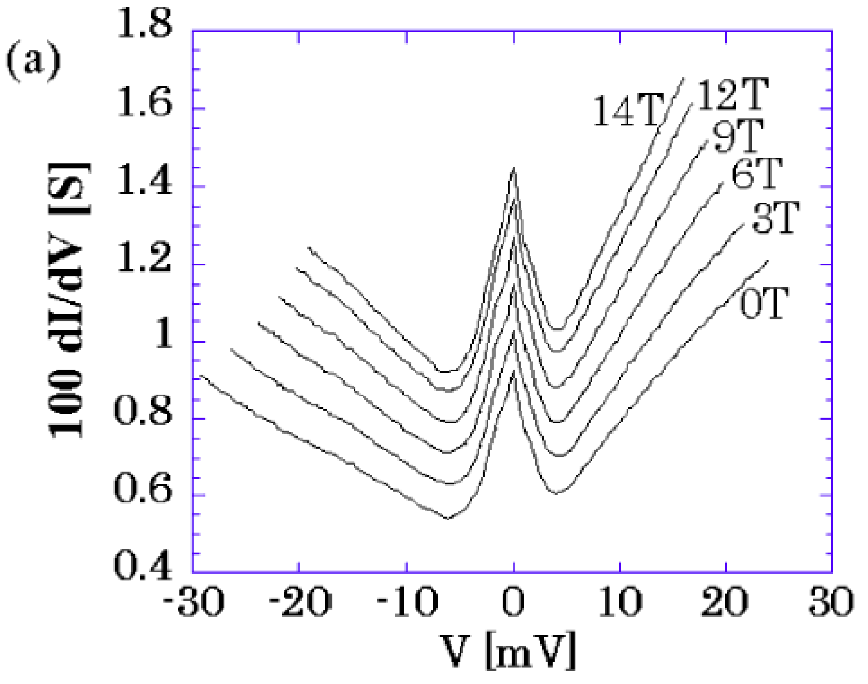


Resonant states
in normal metal.



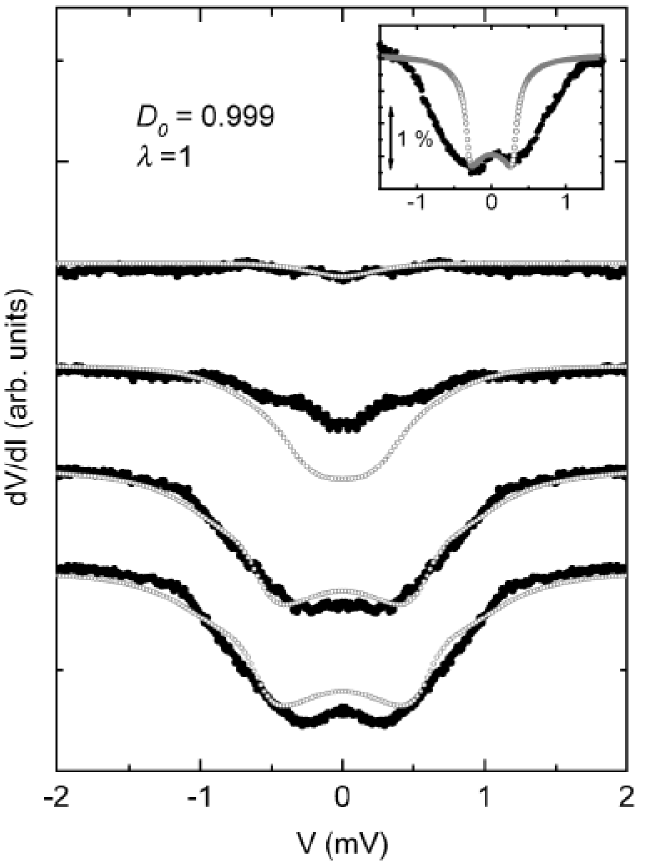
SABS are intrinsic to surface of
anisotropic BCS states.

Zero bias conductance peak



tunneling of YBCO junction

Kashiwaya *et al.*
PRB **70**, 094501
(2004)

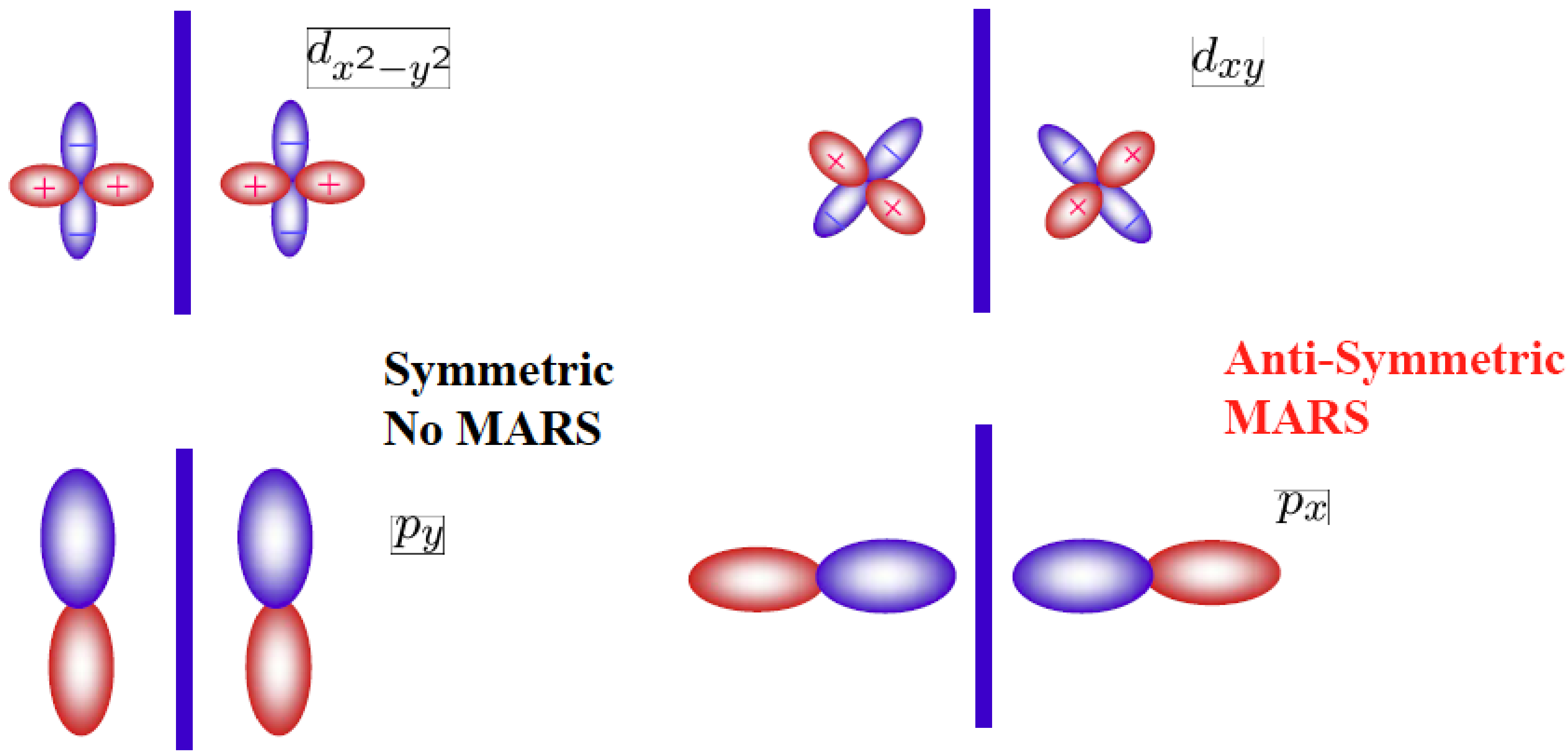


Sr2RuO4

Laube *et al.*
PRL 84,
1595 (2000)

Condition of the formation of mid gap Andreev resonant state(MARS)

Inversion at the plane parallel to the interface

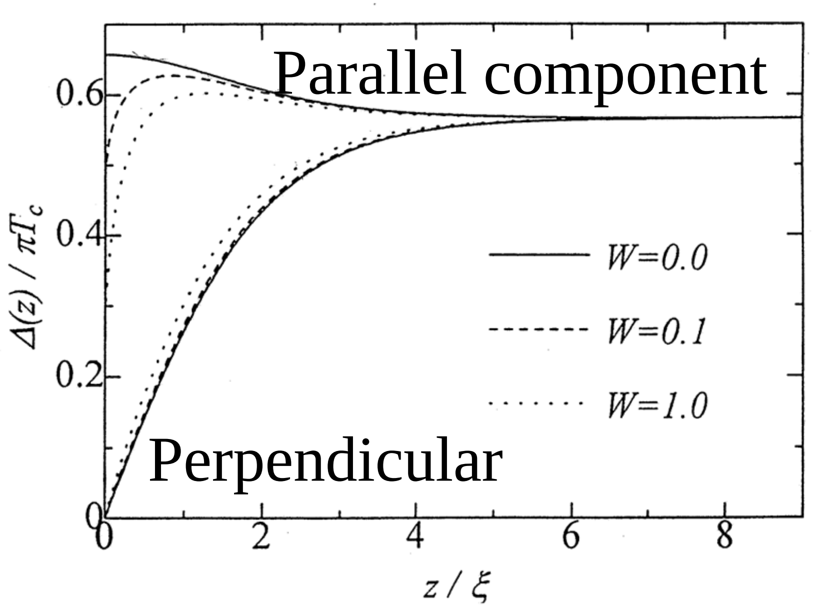


By Yukio Tanaka, superclean (2005)

In BW states, anti-symmetry is broken

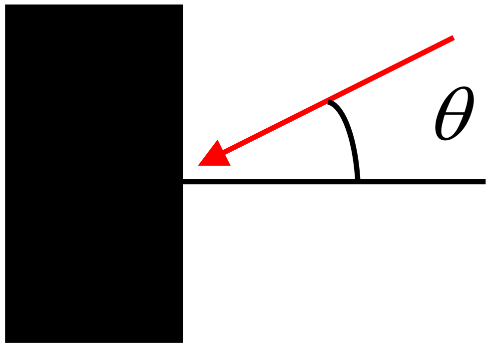
$$\Delta_{\sigma\sigma} = \sigma p_x + i p_y$$

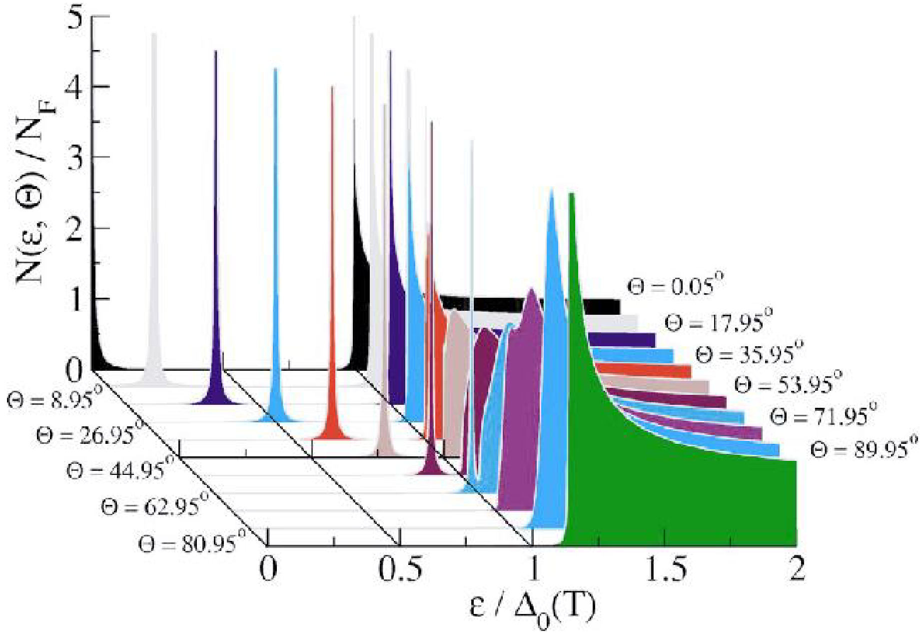
No sharp peak at zero energy but
a broad SABS band appears.



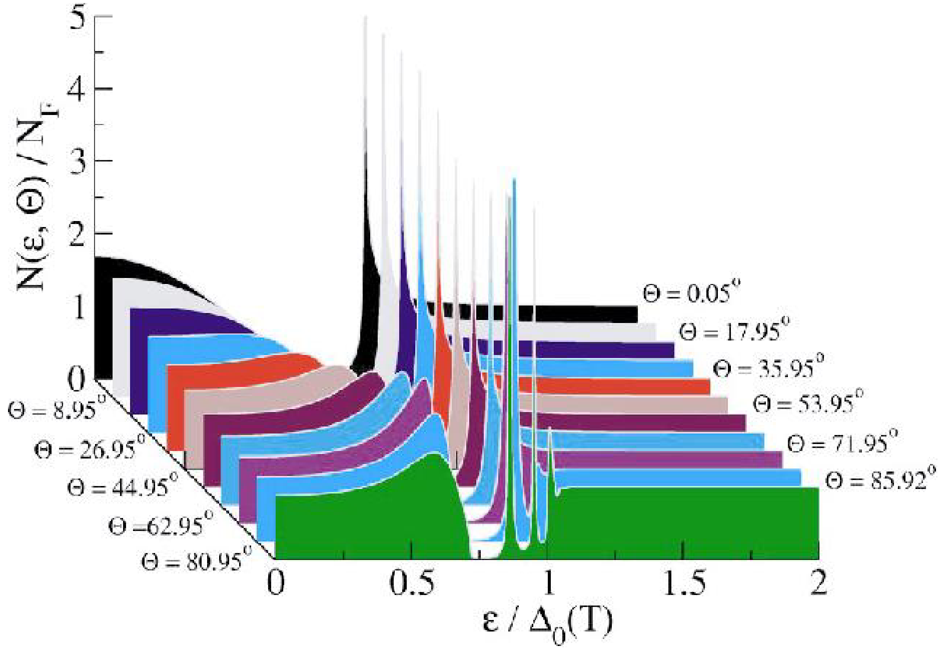
$$d_{\mu i} = \begin{pmatrix} \Delta_{\parallel} & 0 & 0 \\ 0 & \Delta_{\parallel} & 0 \\ 0 & 0 & \Delta_{\perp} \end{pmatrix}$$

$$\varepsilon = \Delta_{//} \sin\theta$$



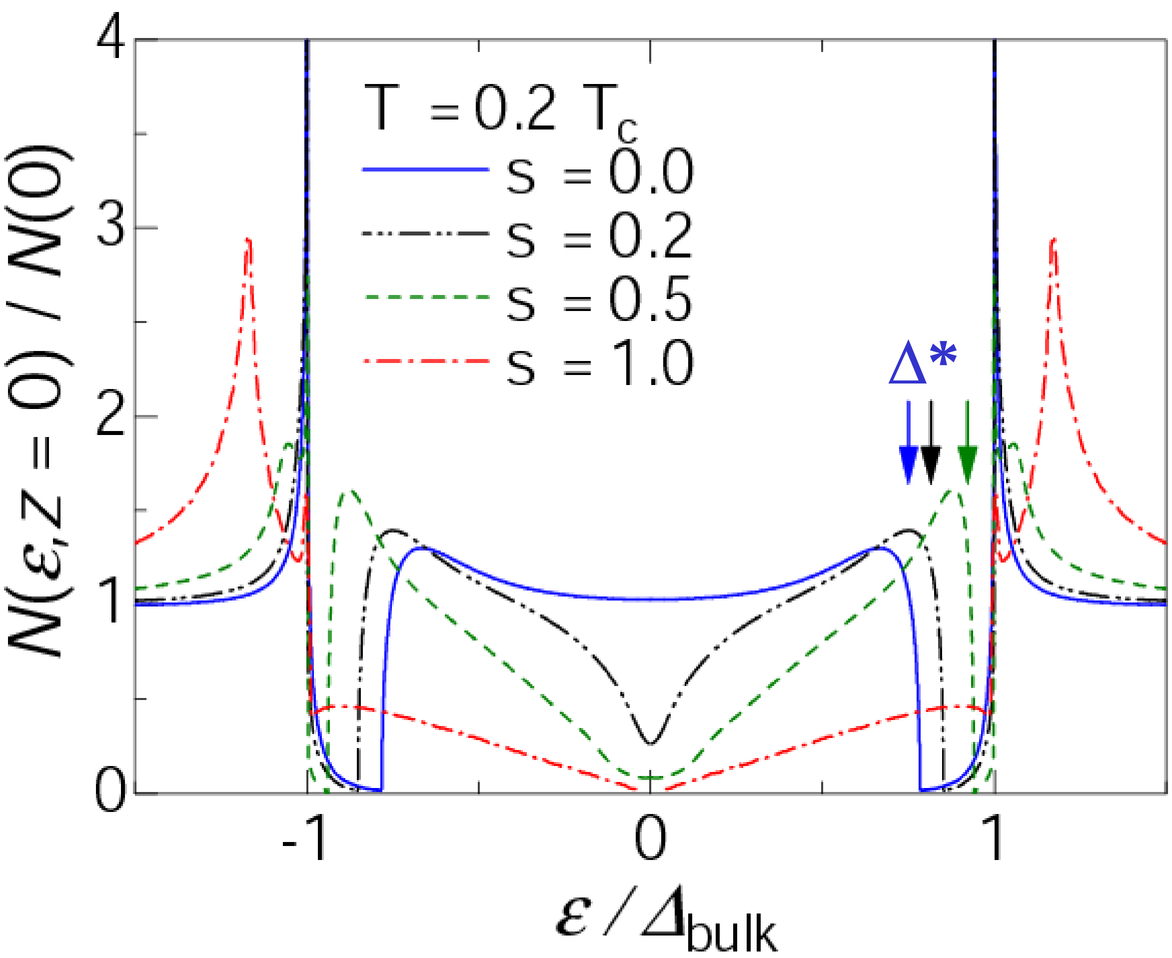


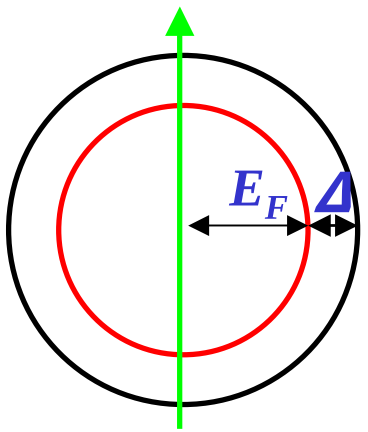
$$\varepsilon = \Delta_{//} \sin\theta$$



Vorontsov, Sauls, 2003

SDOS in BW state





Zero energy state is intrinsically suppressed at S > 0.

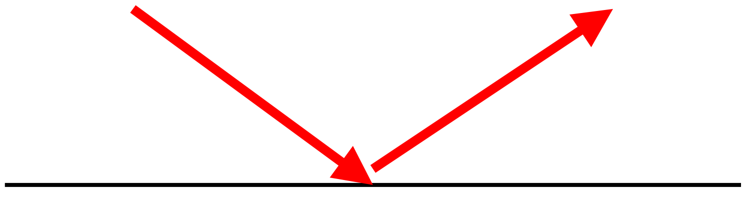
Bandwidth (Δ*) is broader at S > 0.

Flat surface bound states band at S = 0.

Nagato *et al*. JLTP 1998

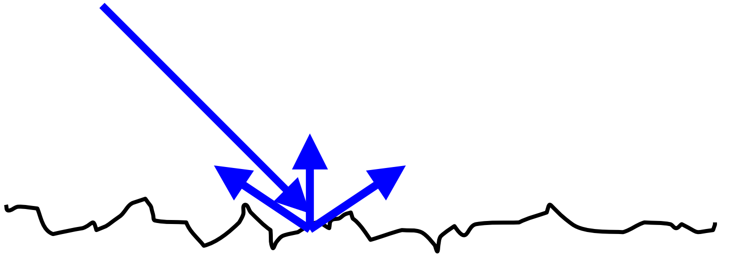
Quasiparticles scattering by a wall

Specular limit



S = 1

Diffusive limit



S = 0

S can be controlled continuously
by thin ^4He layers on a wall.

Measurements

Transverse acoustic impedance of AC-cut quartz in ^{3}He

$$Z = \frac{\Pi_{xz}}{u_x} = Z' + iZ''$$

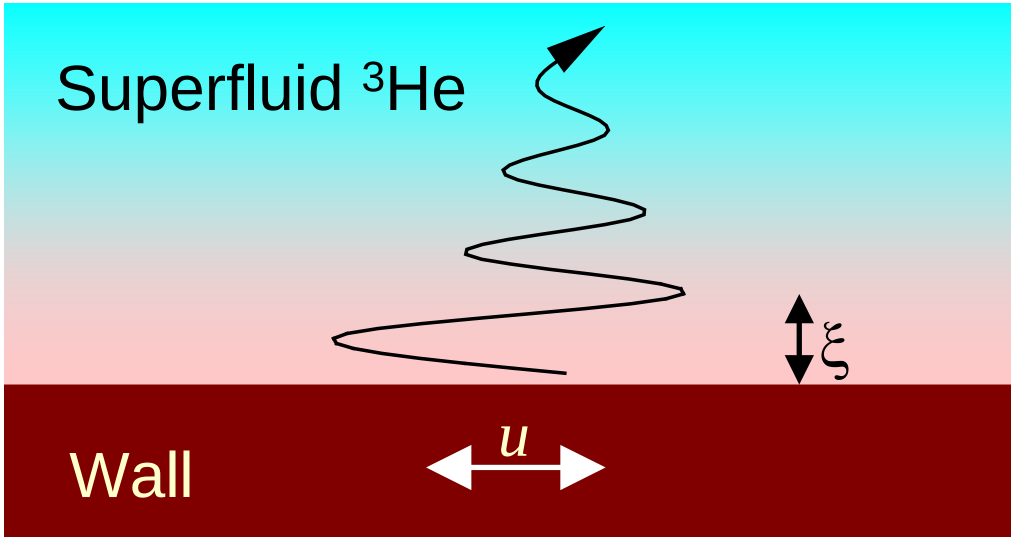
Π_{xz} Stress tensor

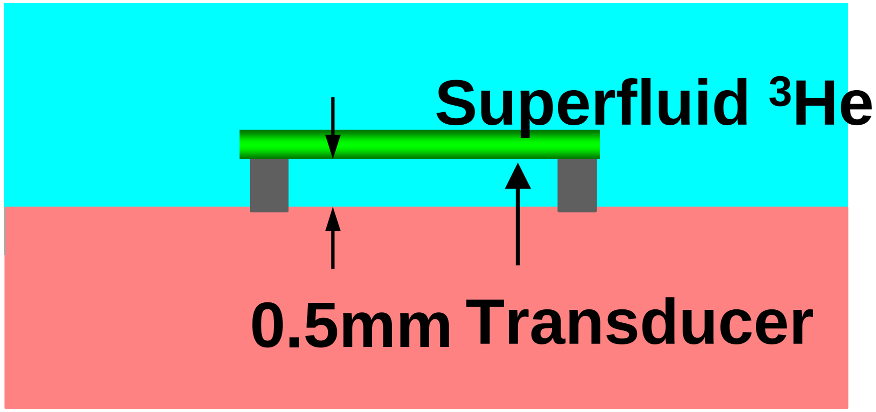
u_x Oscillation velocity

$$Z' - Z'_0 = \frac{1}{4} n\pi Z_q \left(\frac{1}{Q} - \frac{1}{Q_0} \right)$$

$$Z'' - Z''_0 = \frac{1}{2} n\pi Z_q \frac{f - f_0}{f_0}$$

$$Z_q = \rho_q c_q$$





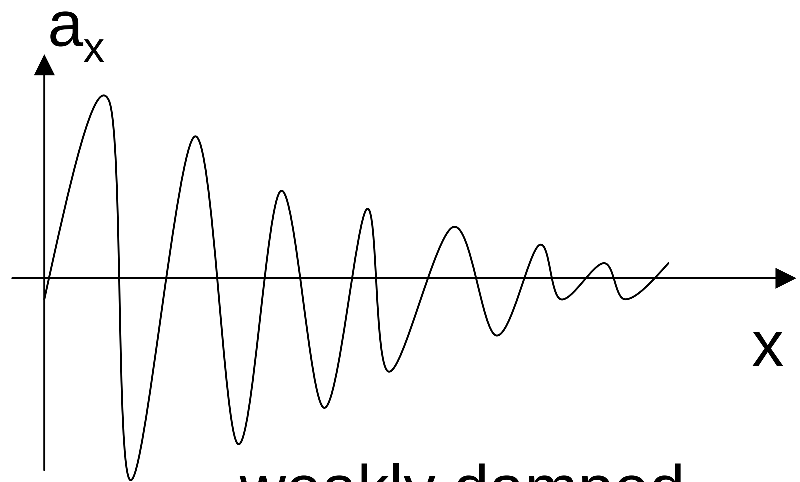
Hydrodynamics region $\omega\tau << 1$

Longitudinal

$$Z = \rho C$$

$$C = c - i\frac{c^2\alpha}{\omega}$$

Equivalent to *c* velocity and α damping measurements

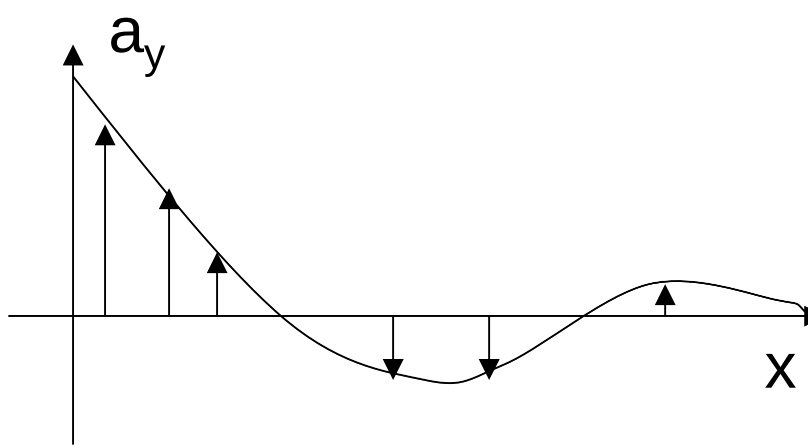


weakly damped

Transverse

$$Z = \sqrt{\frac{\omega\rho\eta}{2}}(1 - i)$$

Equivalent to η viscosity measurements



critically damped

2. Review on SABS in B phase

In B phase

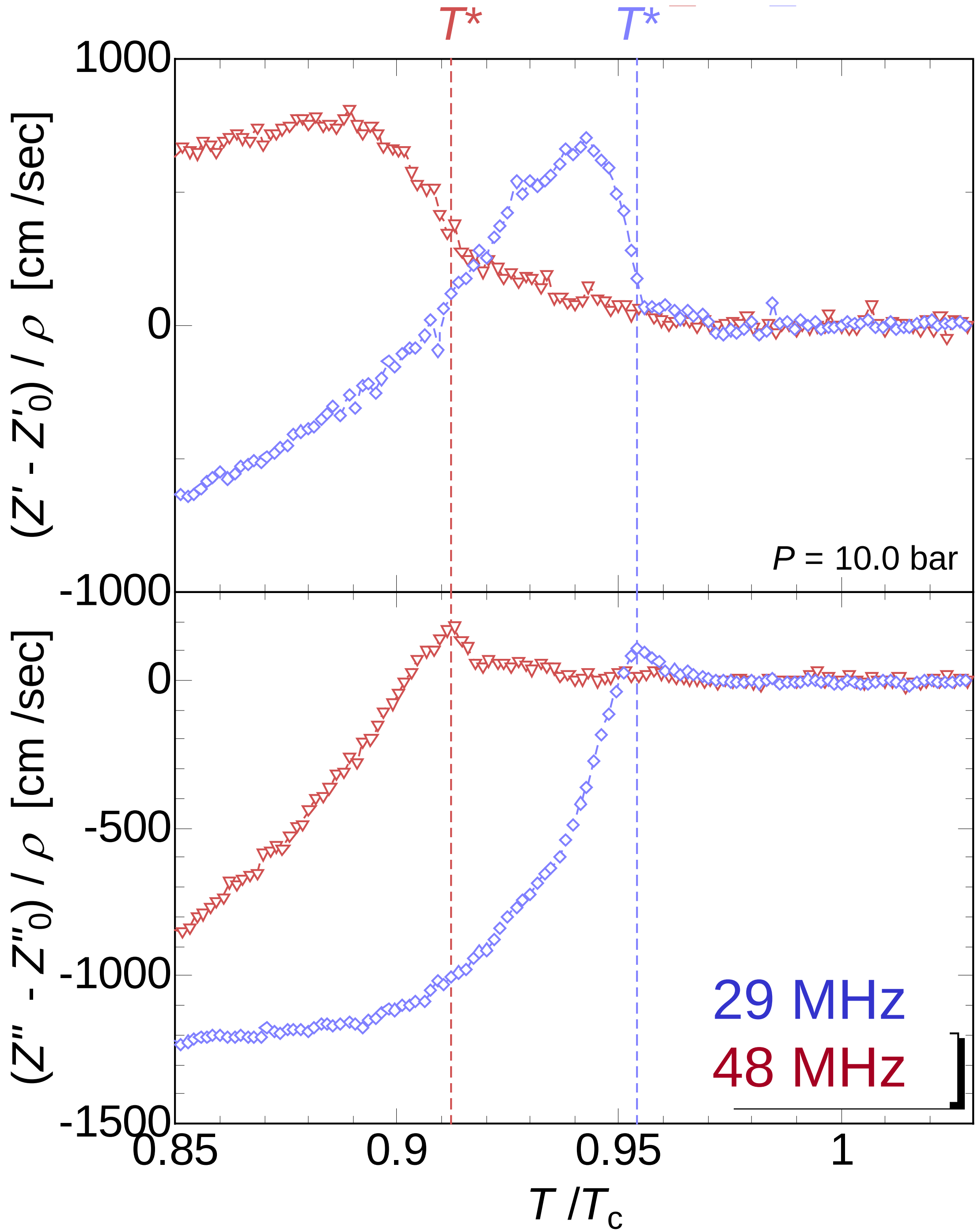
No change in Z at T_c

No drop in Z' at T_{pb}.

peak in *Z"* and kink in *Z'* at *T**

Broad peak in Z' at low T.

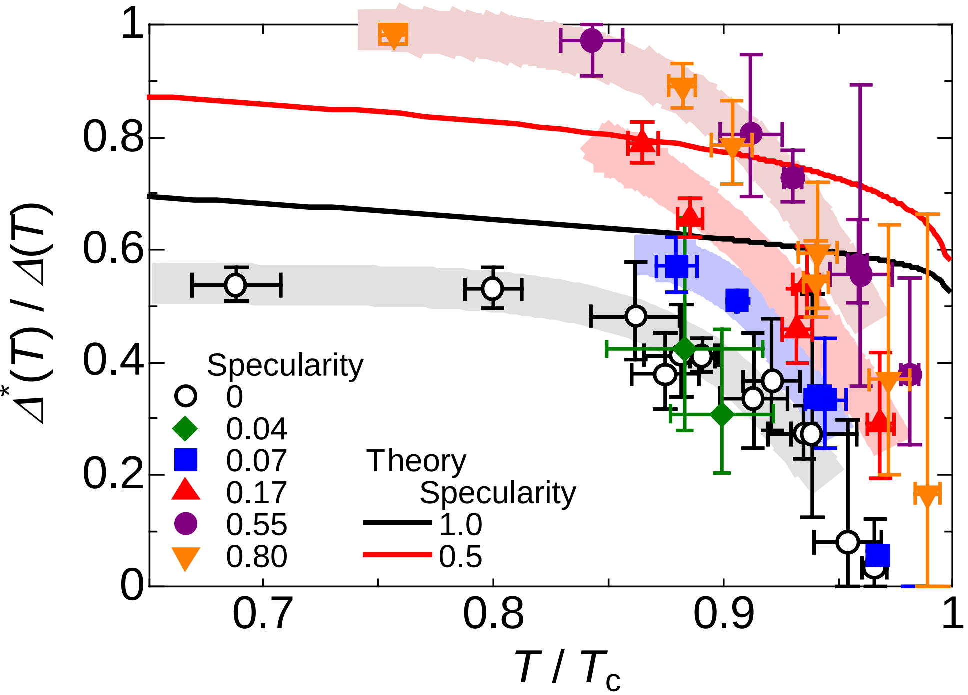
$$\hbar\omega = \Delta + \Delta^*$$



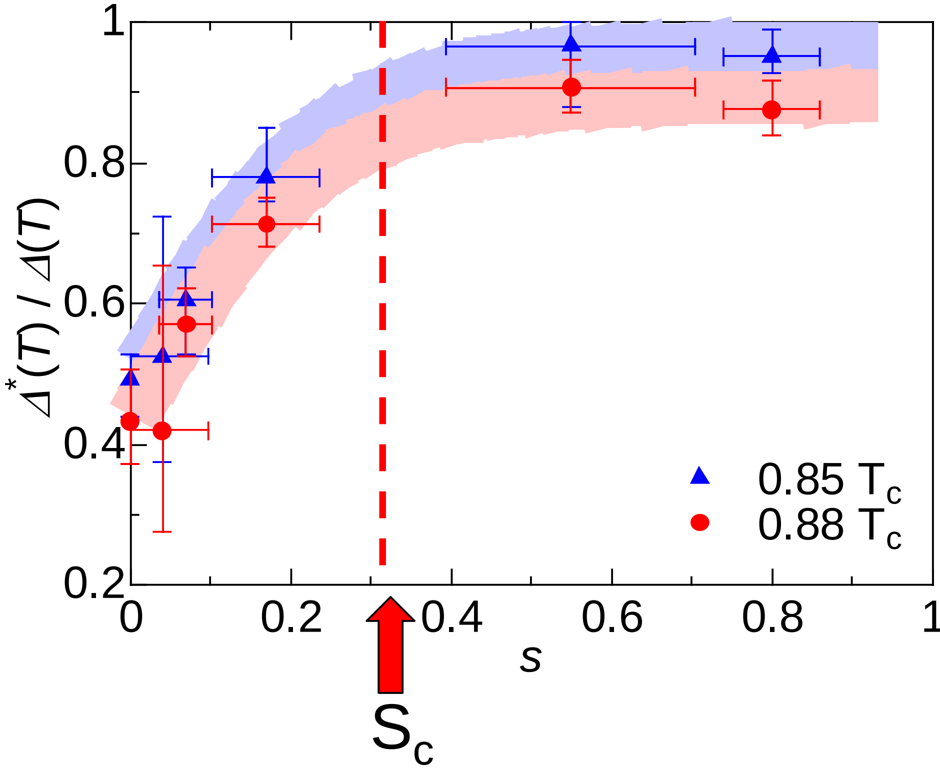
Aoki et al. PRL 2005

S dependence of $\Delta^*(T)/\Delta(T)$

Temperature dependence



isotherm



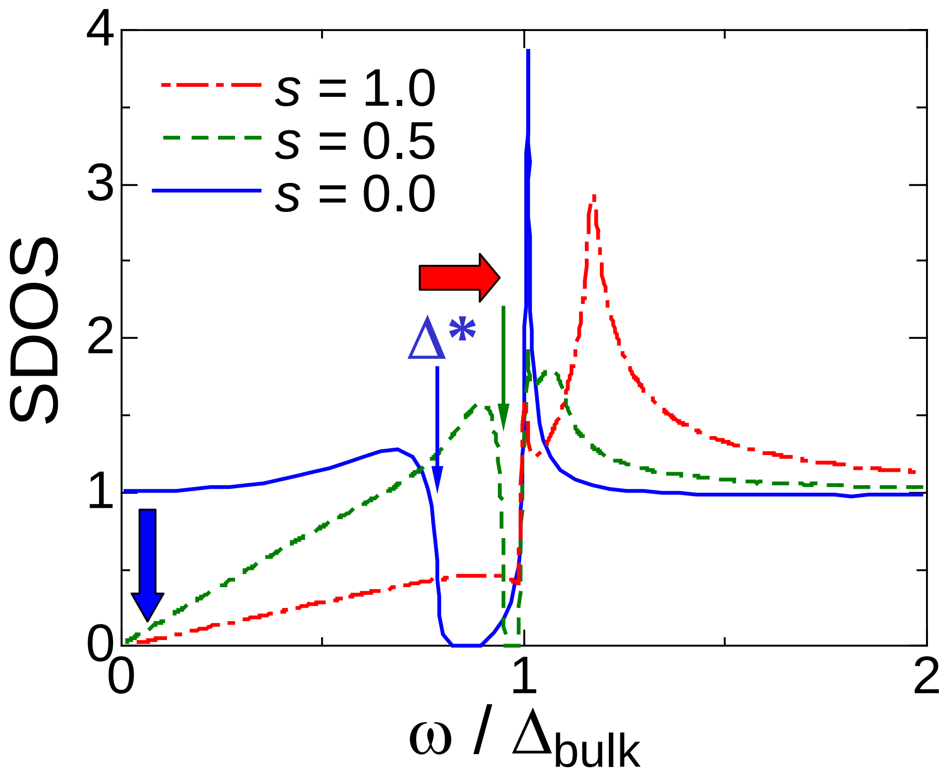
Wada *et al*., PRB **78**, 214516 (2008)

Z(ω/Δ)

single peak

Murakawa *et al*. to be published

Summary 2



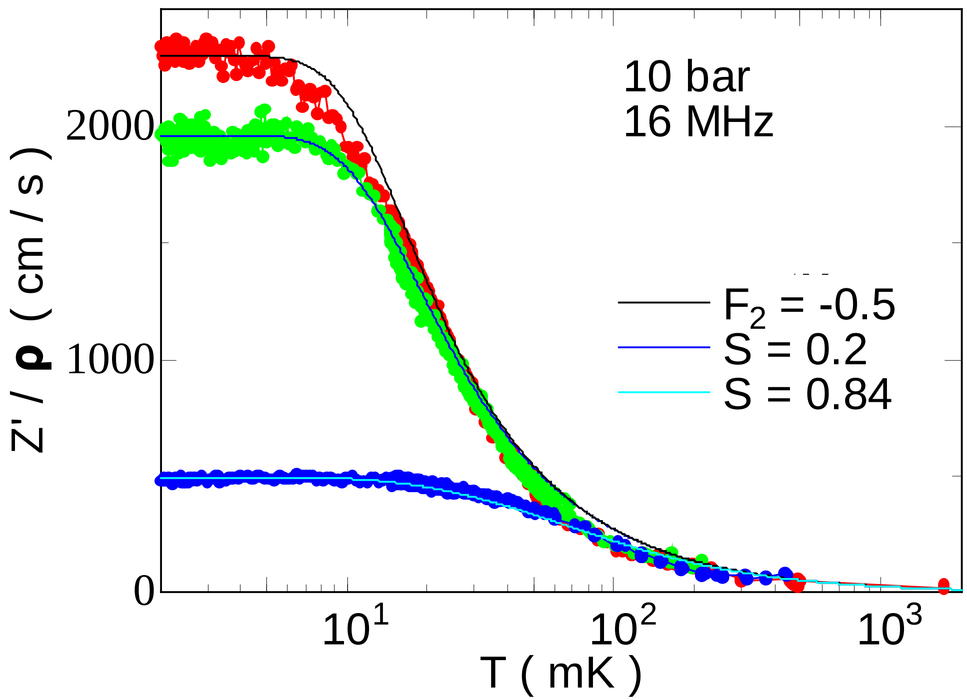
Broadening at larger S

Suppression of SDOS at Fermi energy at larger S

Nagato *et al*. JLTP 1998

3. Superfluidity of 4He films pressurized by 3He.

Evaluate S from *Z* in normal fluid



pure

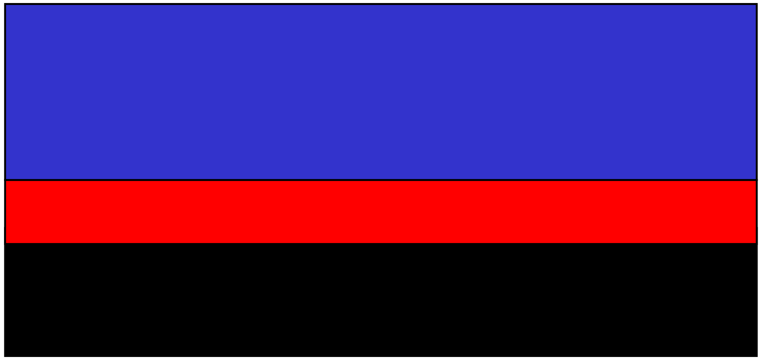
2.7 layers

3.5

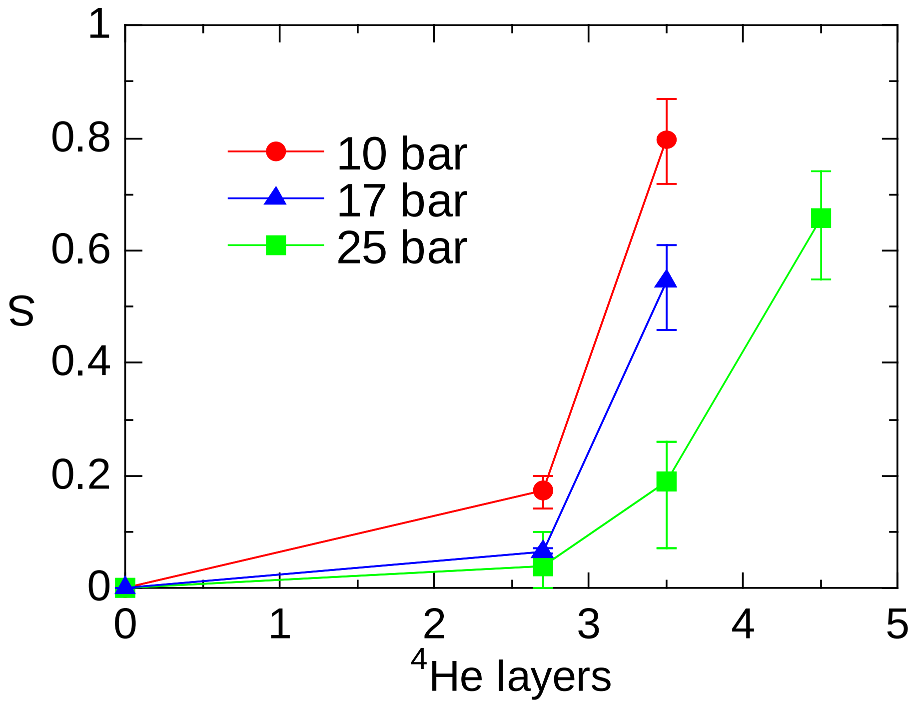
3He

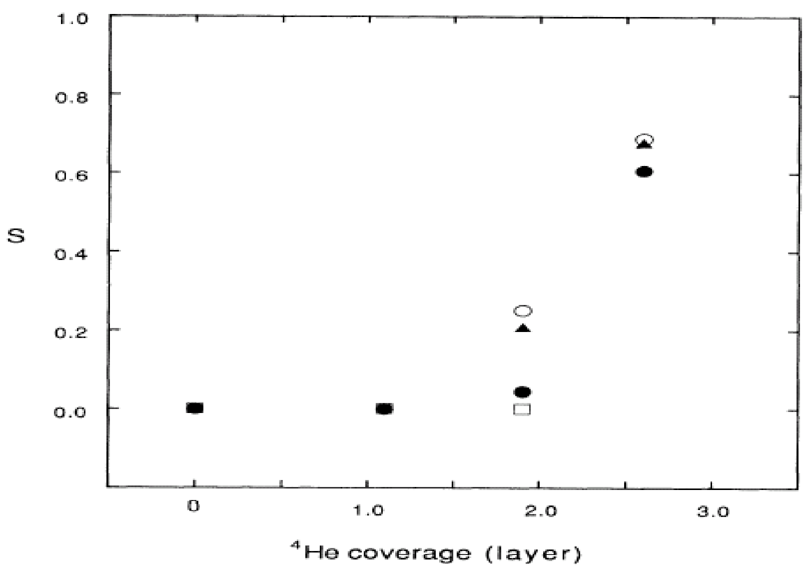
4He

wall



S vs ^{4}He layers and P





D. Kim *et al,* PRL(1993)

S is larder for thicker ^{4}He.

is smaller at higher P.

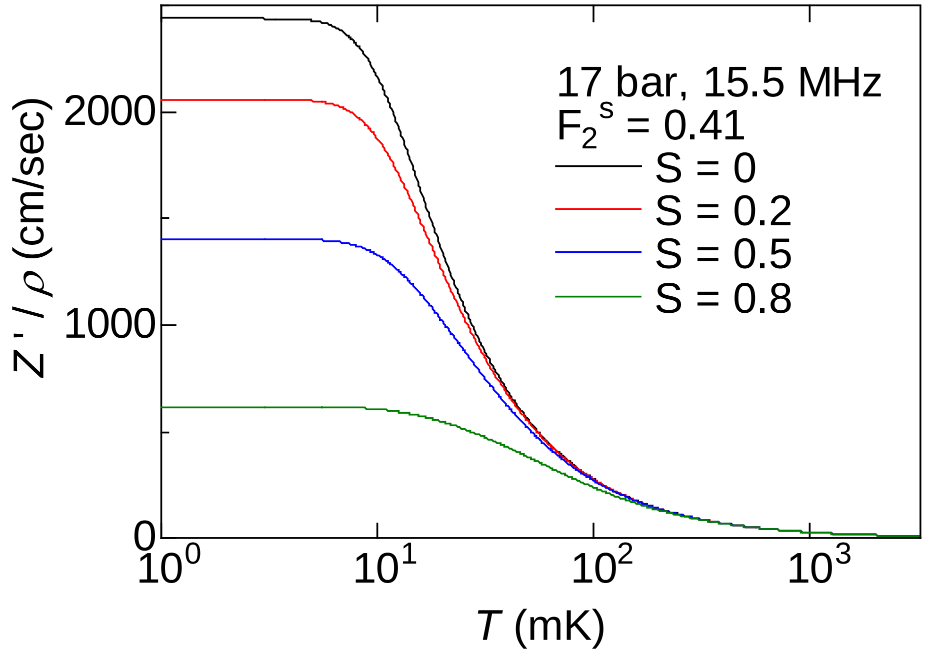
Z in normal 3He with 4He coating

pure

2.7 layers

3.5

4.5



Theory

Z' deviates and decrease at low T.

S is temperature dependent.

Is Tc superfluid transition temperature of 4He?

4He layer dependence

2.7 layers

3.5

4.5

layers

Pressure dependence

25 bar
17
10

2.7 layers
3.5
4.5

P

Frequency dependence

Tc depends on frequency.

KT-like

10bar layer2.7

$$\frac{T_{\mathrm{c}} - T_{\mathrm{KT}}}{T_{\mathrm{KT}}} = \frac{4\pi^2}{b^2}\left(\frac{1}{2}\ln\frac{14}{2\pi f}\frac{D}{{a_0}^2}\right)^{-2}$$

Dynamic KT theory

D: diffusion constant

a_0: core radius

Preliminary analysis by Hieda
at Nagoya Univ.

● ● Hieda et al. JPSJ 2009

Summary 3

S increases below Tc.

KT transition or other?

Pressure effect on Tc?

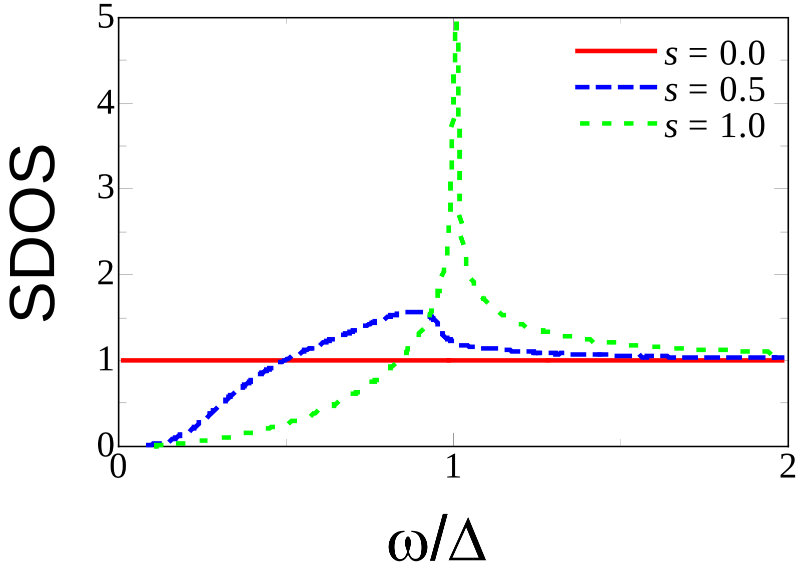
3He dissolved.

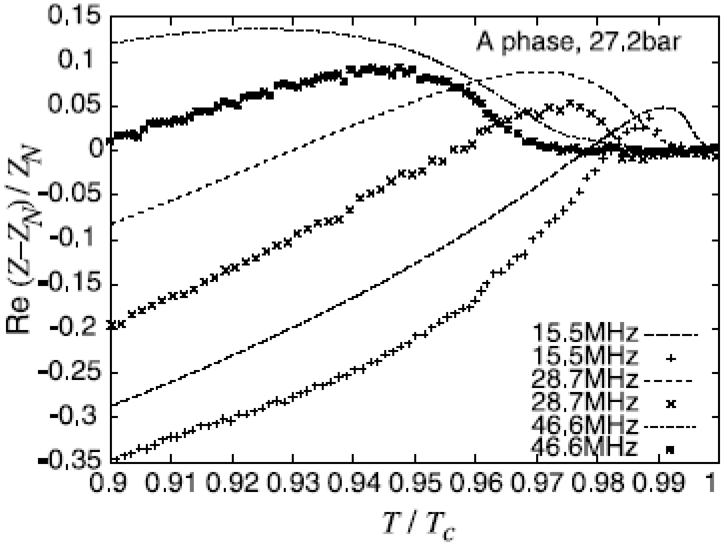
Increase of inert layers.

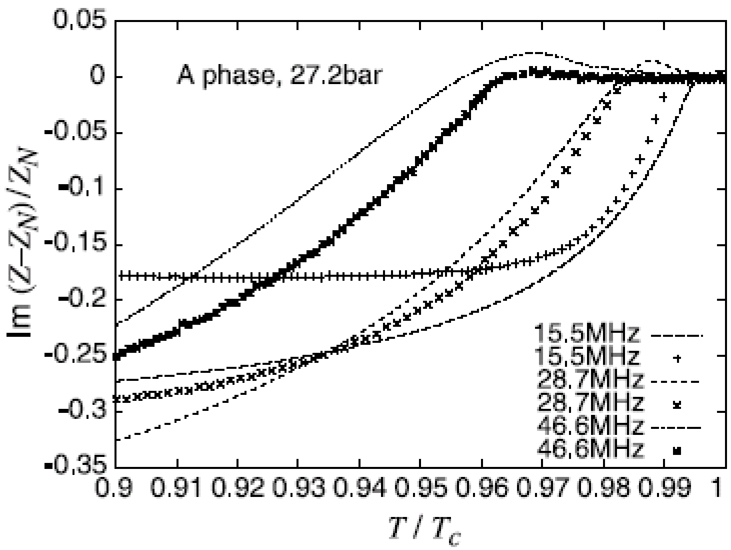
Strong correlation effect.

4. Acoustic response of superfluid 3He at high magnetic field.

A phase at 0 field.



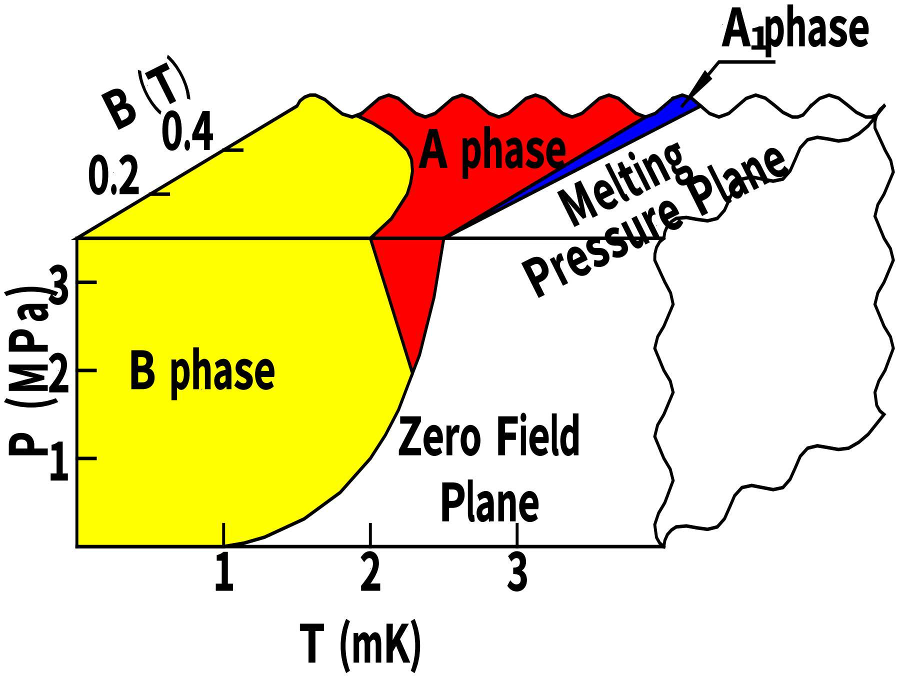


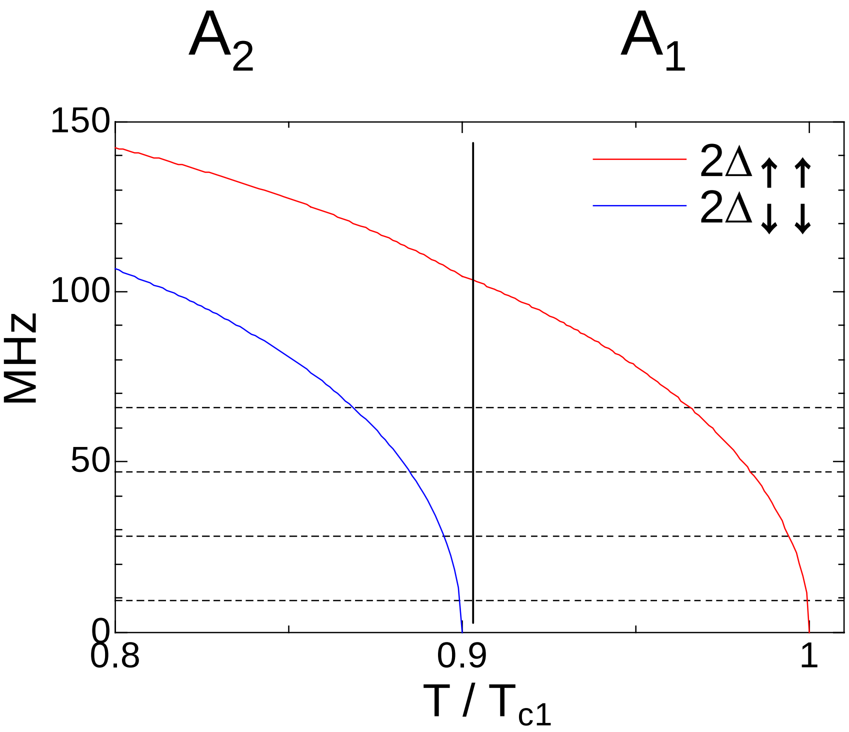


Theory includes surface states.

Saitoh, *et al*. PRB(R) 2006

Nagato, *et al*. JLTP 2007


A1 phase
B (T)
0.4
0.2
A phase
Melting
Pressure Plane
B phase
Zero Field
Plane
P (MPa)
3
2
1
1
2
3
T (mK)


A2
A1
150
100
50
0
MHz
2Δ↑↑
2Δ↓↓
0.8
0.9
1
T / Tc1

A_2 A_1

Frequency
dependence
at 5 T

experiment

9.42 MHz

28.3 MHz

47.1 MHz

66.0 MHz

A_2 A_1

Frequency dependence, theory

9.42 MHz

28.3 MHz

47.1 MHz

66.0 MHz

Nagato *et al.* unpblished

Magnetic field dependence, experiment

0.6 T

5 T

10 T

Magnetic field dependence, theory

0.6 T

5 T

10 T

Weak coupling limit; $\Delta_{\downarrow\downarrow}$ and $\Delta_{\uparrow\uparrow}$ are independent.

Nagato *et al*. unpublished

30 MHz

Theory neglect the strong coupling effect.

Magnetic scattering effect ?

Any metastable state in A_2 phase?

Summary 4

Drop in Z is larger in A_1 phase than in A_2 phase.

This anomalous asymmetry is pronounced at high frequency.

At 10 MHz, Z sometimes increases rather than drops.

A new manifestation of strong coupling effect?