Experimental Search for Majorana Fermion in ^{3}He-B; Achievements and Challenges

Tokyo Institute of Technology

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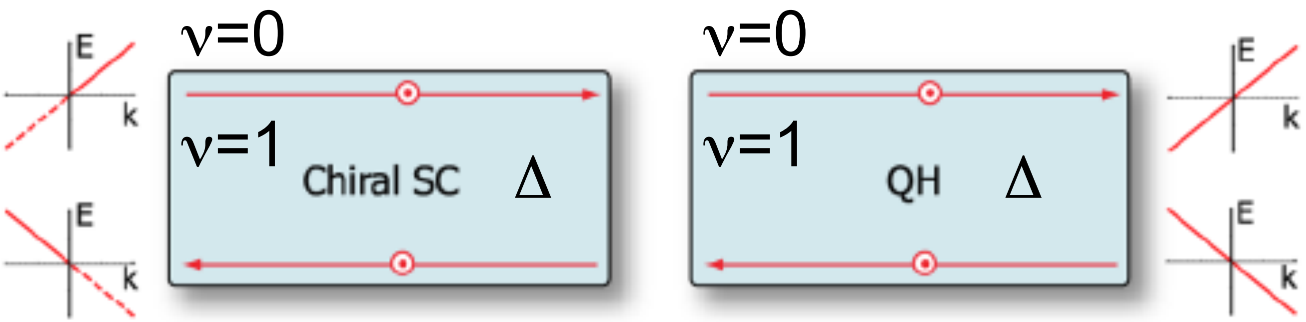
1. Introduction
2. Achievements
3. Challenges

Topological superfluids　　　Topological insulators

T-breaking

2d-A、

Sr_2RuO_4

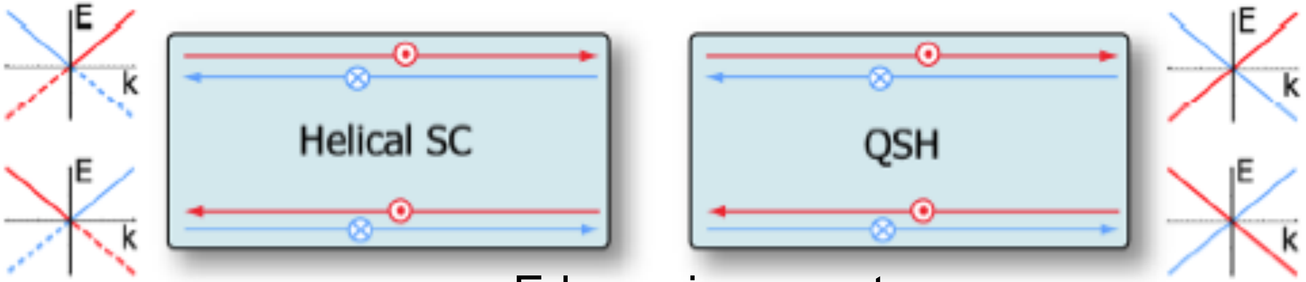


Quantum Hall

Bulk-edge correspondence

Edge current

T-invariant

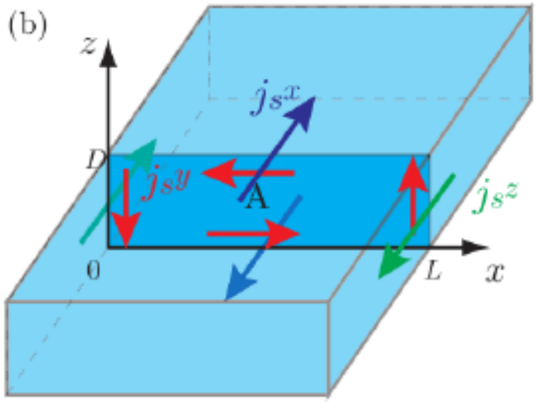


Quantum spin Hall

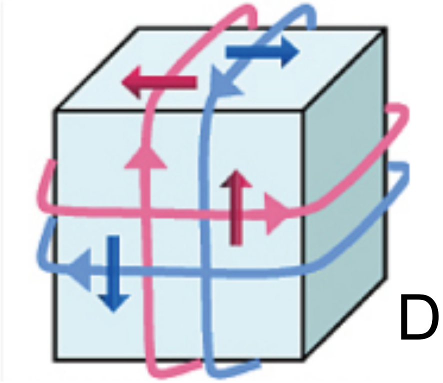
Edge spin current

3d

^{3}He-B



Majorana fermions



Dirac fermions

X. L. Qi, S.C. Zhang, PRL 2009

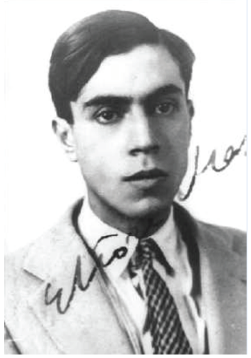
Tsutsumi *et al.,* JPSJ, PRB 2010

Majorana surface states in ^{3}He-B

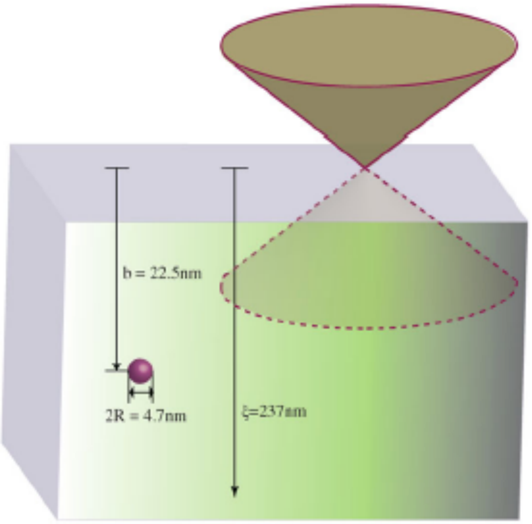
$$\psi = \psi^{+}$$

particel = anti-particel

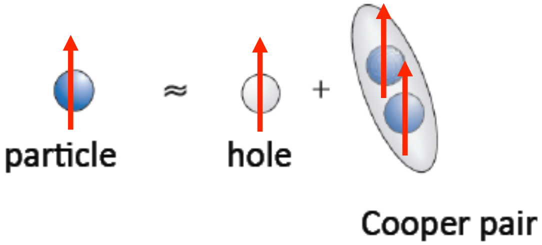
SABS: Majorana Fermion

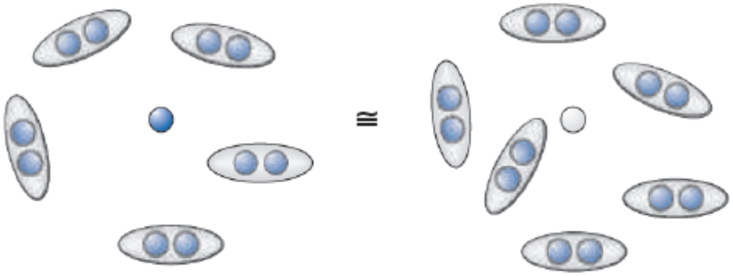


"Majorana cone"



Chung and Zhan, PRL09





Wilczek, Nat. Phys. 5, 614 (2009)

	Bulk order parameters	Surface states
(Triplet) Superconductors	Difficult to determine ← (complicated by charge, multi-band, defects, impurities, magnetism,…)	Tunneling conductance
Spin-triplet p-wave Superfluid ^{3}He	Well established → (simple, clean,…)	No good surface probe (until recently)

^{3}He: Good testing ground for topological quantum physics!!

Our measurements

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

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

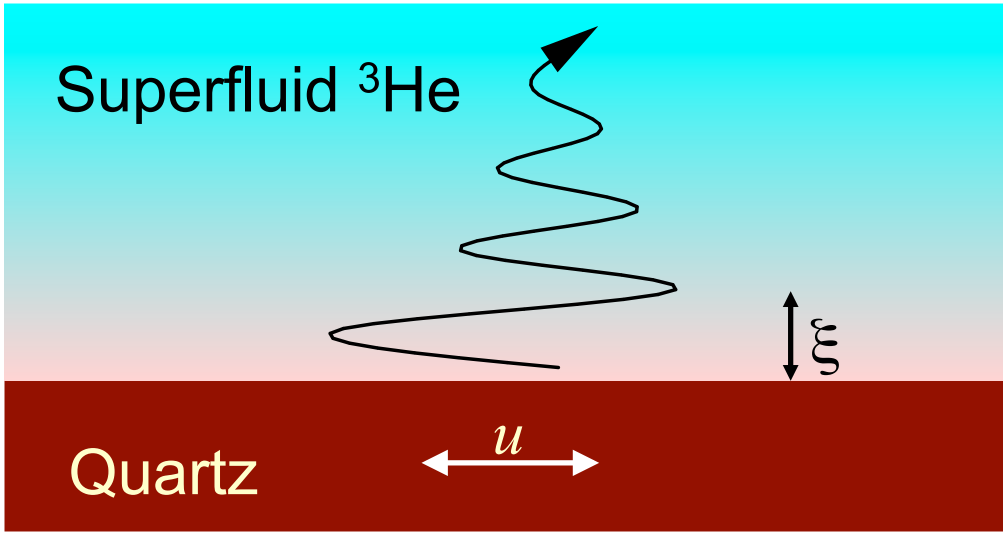
Π_{xz} Stress tensor of liquid on quartz

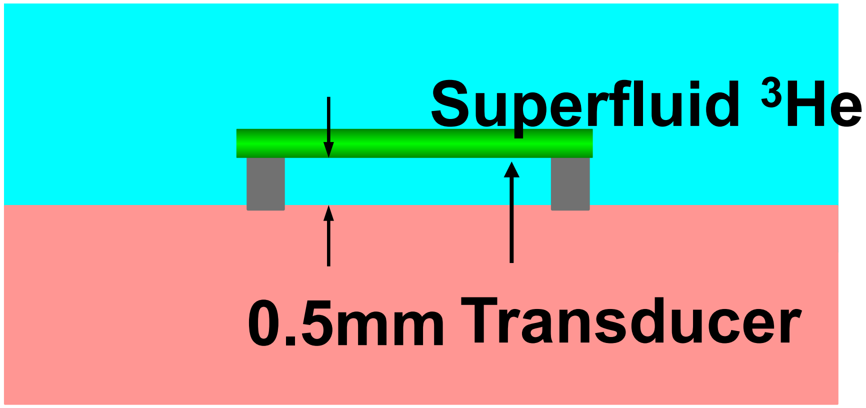
u_x Oscillation velocity

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

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

$$Z_q = \rho_q c_q$$



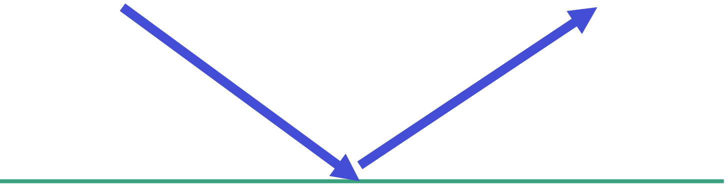


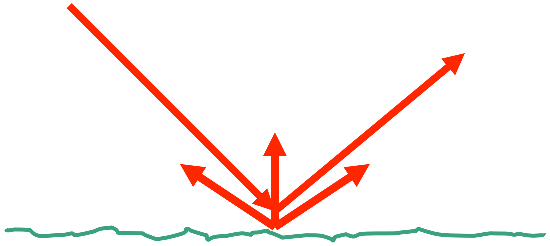
Quasiparticles scattering off a wall

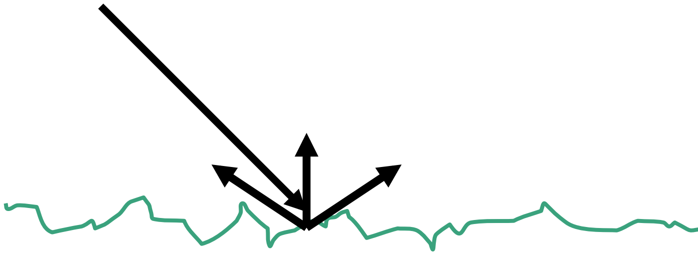
Specular limit

Partially specular

Diffusive limit



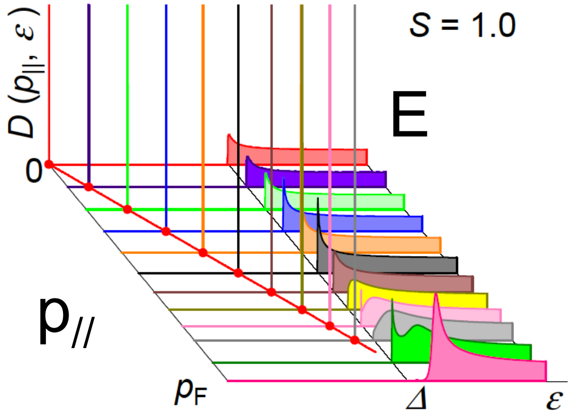


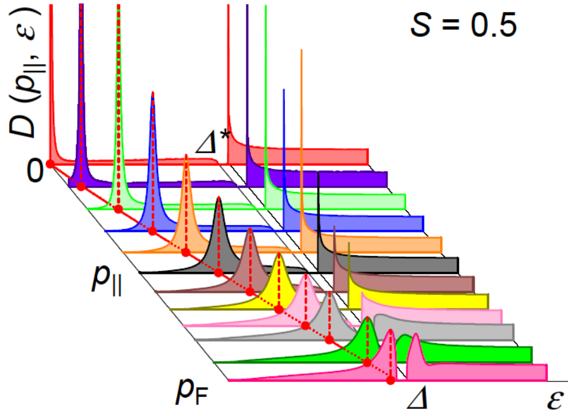


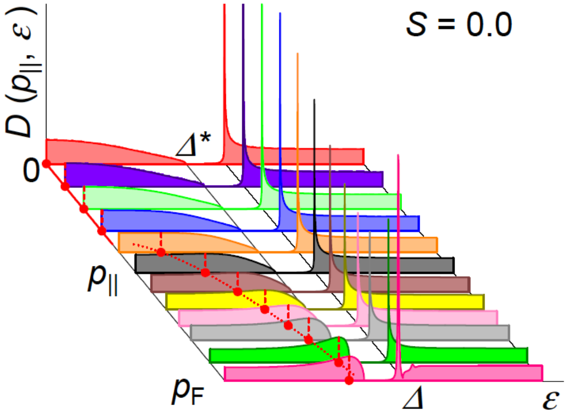
$S = 1$

$1 > S > 0$

$S = 0$







theory

$S = 0.5$

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

Murakawa *et al.*, PRL 2012

B phase at S = 0, H = 0

No change in Z at T_c

↓

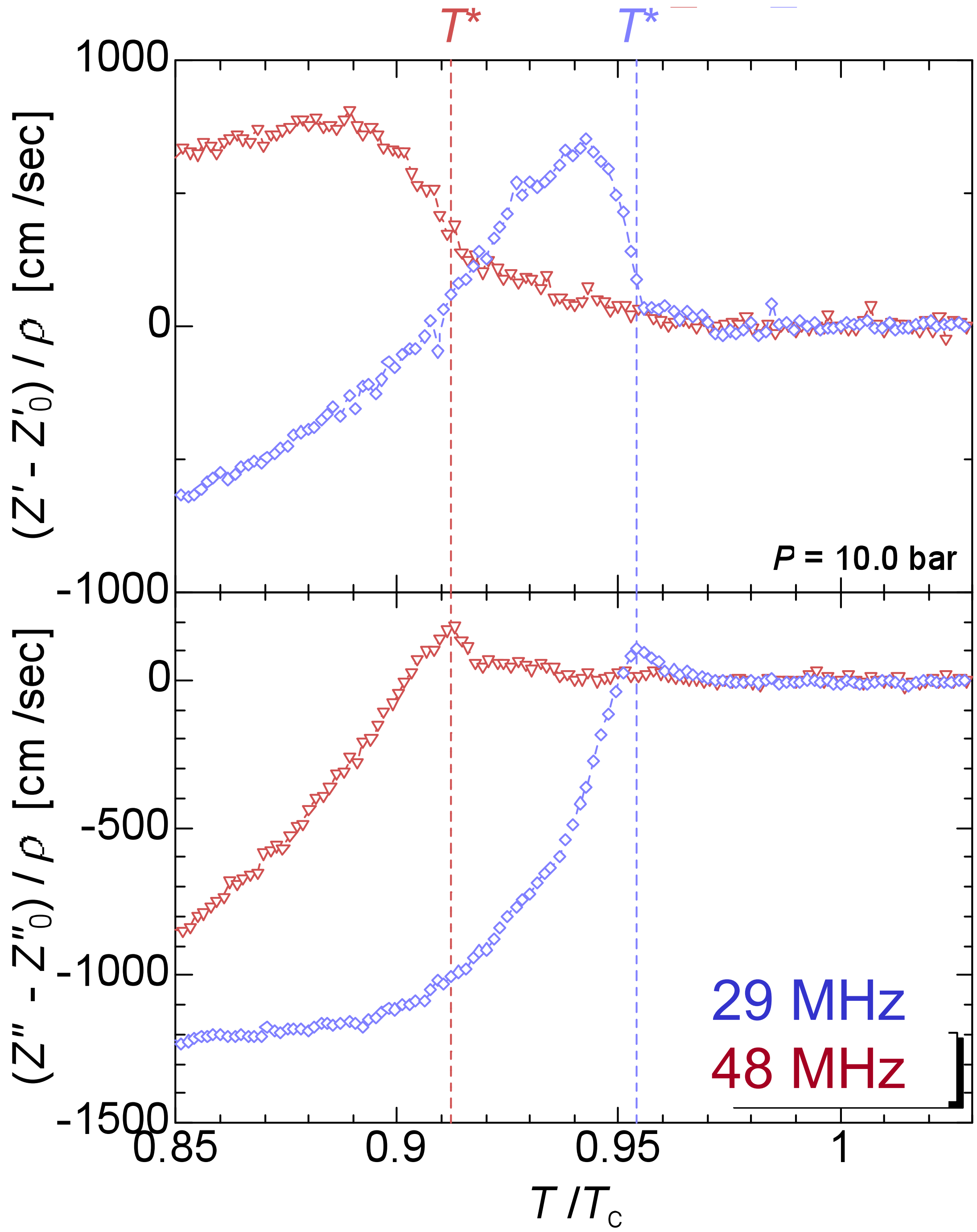
No drop in Z’ at T_{pb}.

↓

peak in *Z*” and kink in *Z’* at *T**

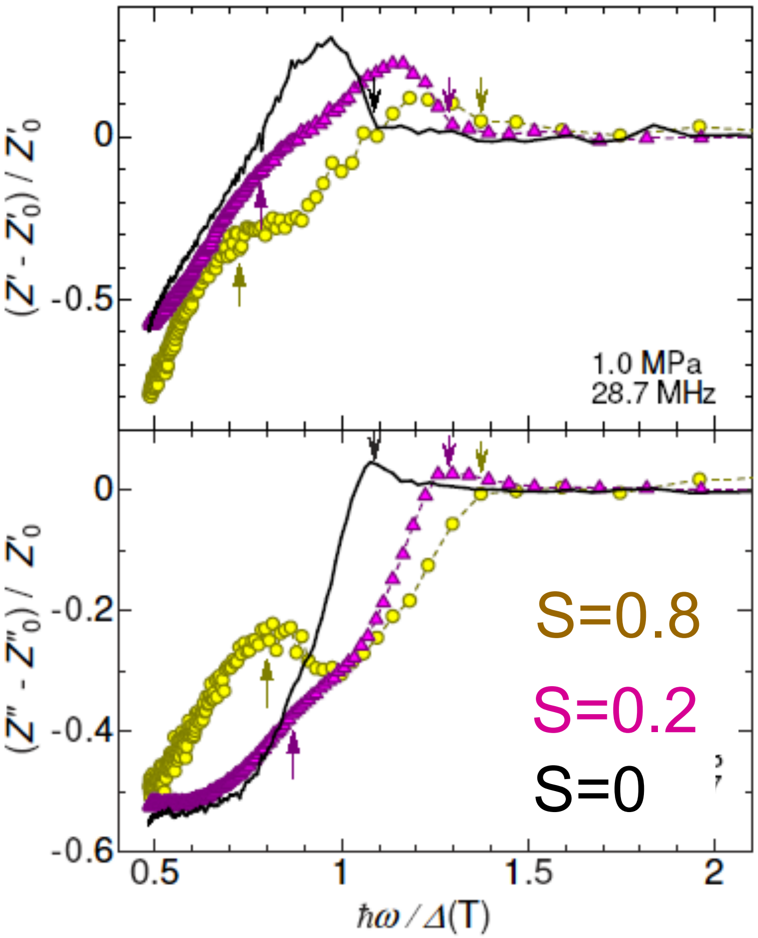
Structure appears below $T_{pb.}$

Low lying excitations !!

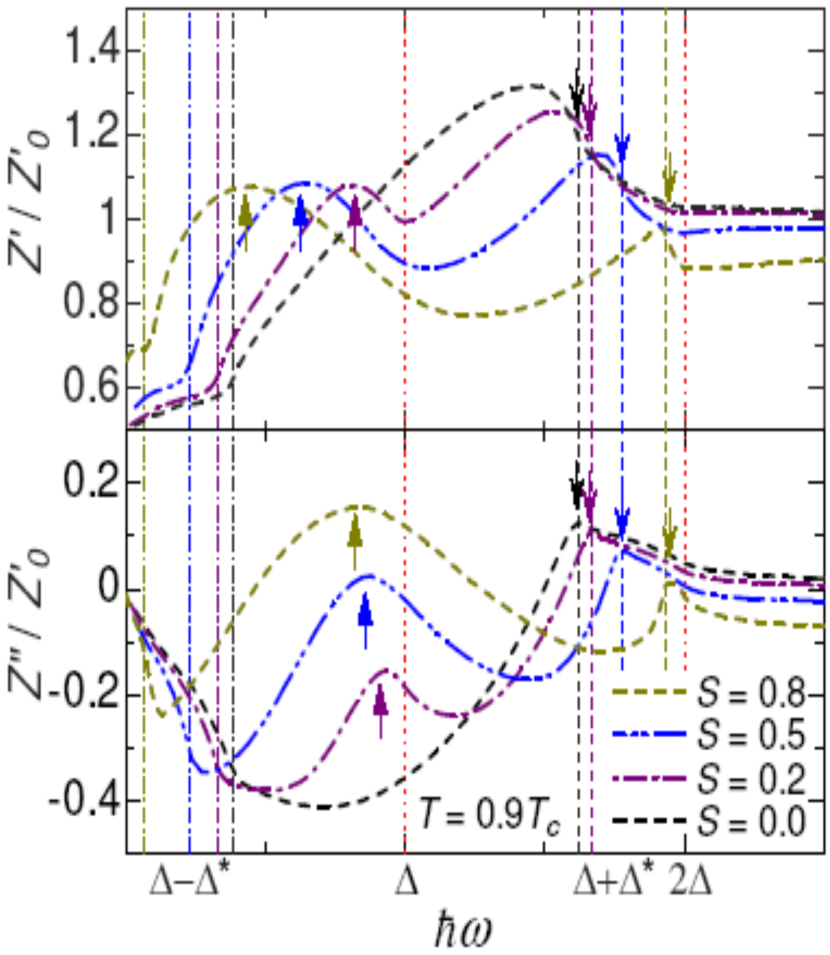


$Z(\omega/\Delta)$ at $S > 0$

experiment



theory



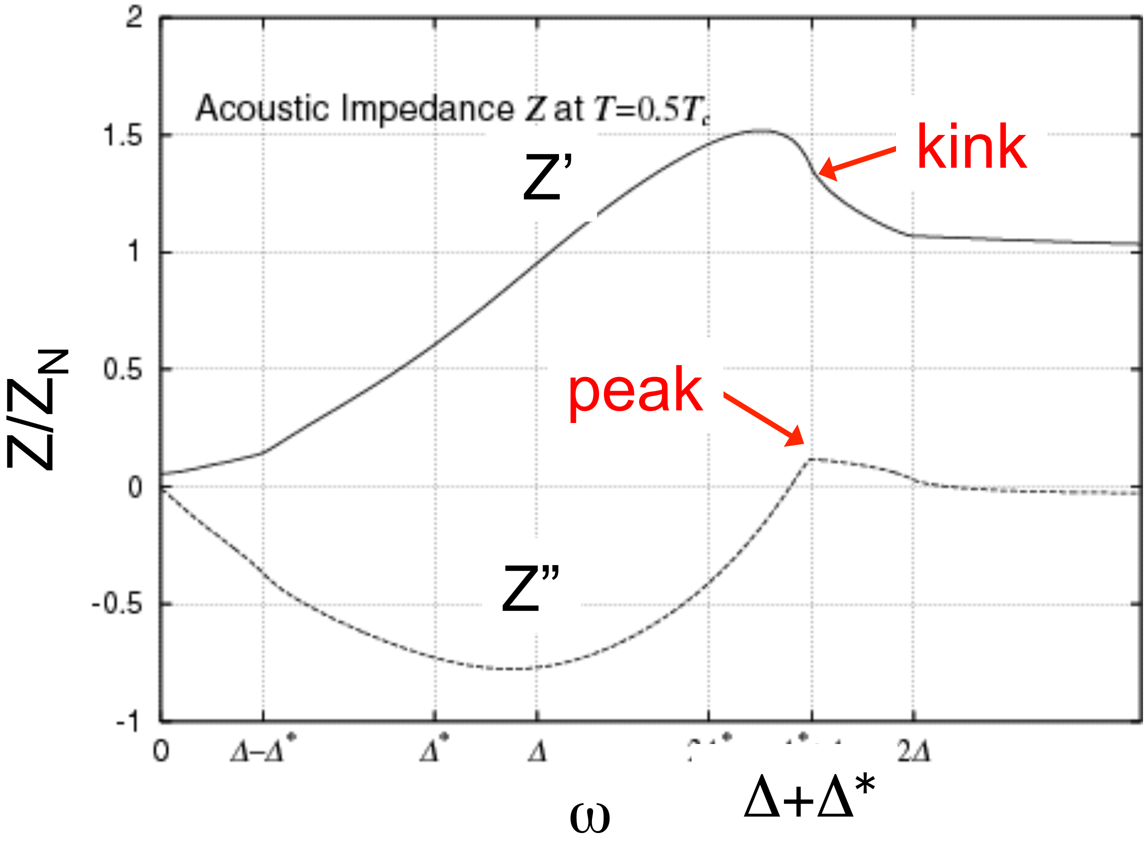
Murakawa *et al*., PRL 2009

Murakawa *et al*., JPSJ 2011

Z(ω) theory with SABS at S = 0

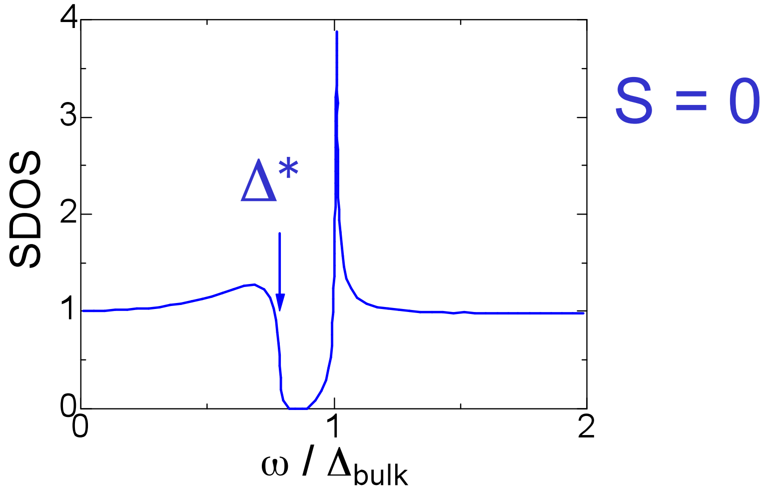
Kink and peak are singularities when $\hbar\omega = \Delta + \Delta^*$

$$\int_0^{\hbar\omega} d\varepsilon N(\varepsilon) N(\hbar\omega - \varepsilon)$$

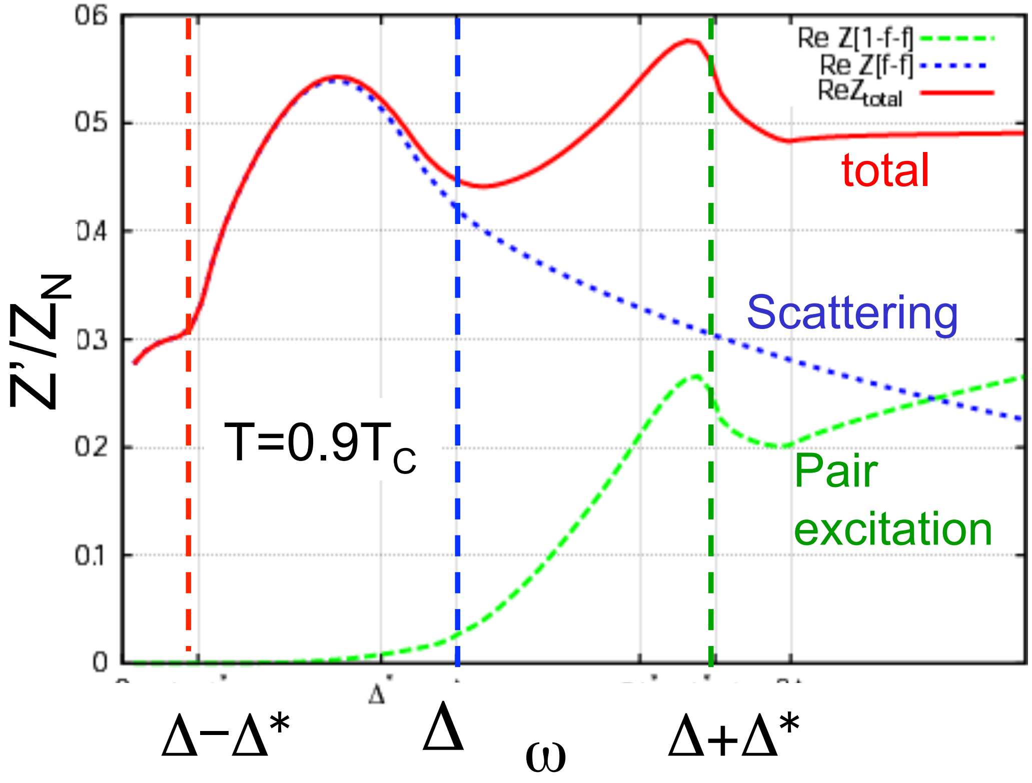


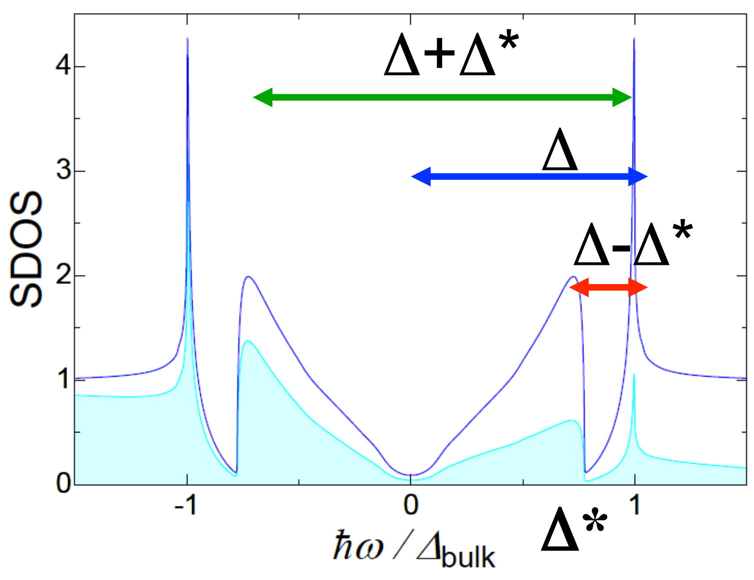
First experimental confirmation of the sub-gap structure.

Aoki *et al*., PRL 2005

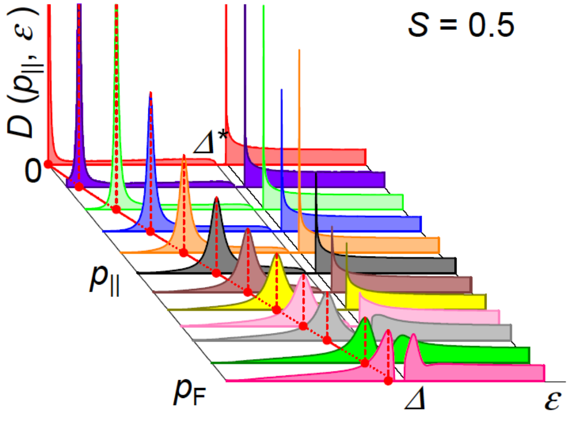


Z(ω) theory by Nagato *et al*. for S = 0.5





^{3}He-B is truly a topological superfluid showing the bulk-edge correspondence at S >> 0.

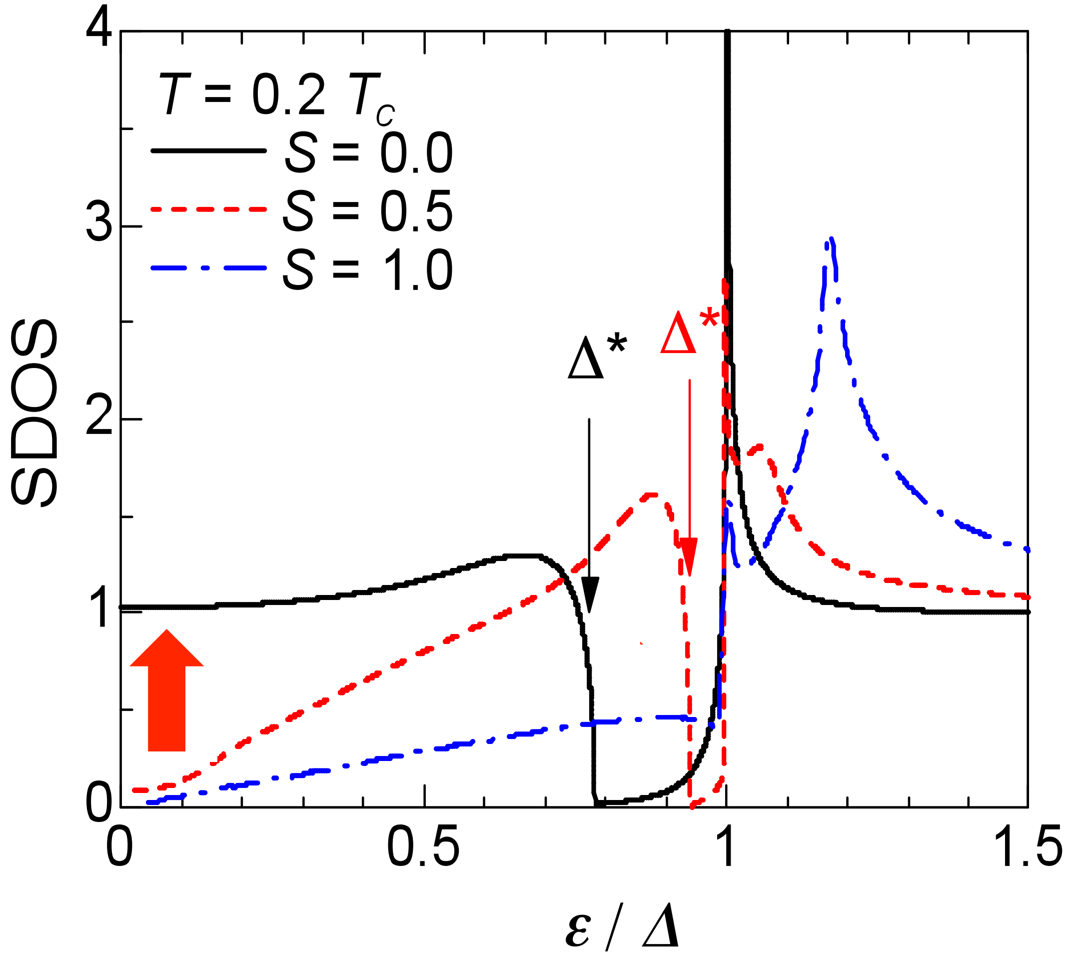


Two peaks in Z(ω) due to the formation of Majorana cone.

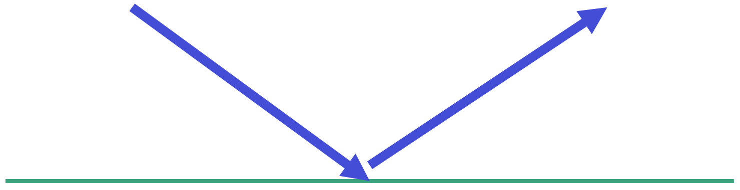
What is a topological nature of the surface states in our measurements?

Usually, particles are localized by the disorder and gap appears at zero energy.
However, topological surface states are not gappable in the presence of disorder.

Theoretically calculated SDOS in BW state at various S

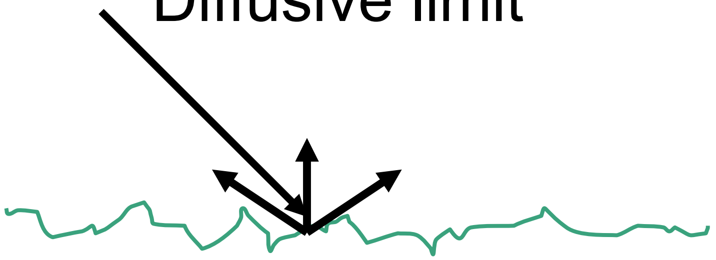


Specular limit



S = 1

Diffusive limit



S = 0

Surface states are not gappable.

Zero modes are robust against disorder.

Topological nature.

Nagato *et al.*, JLTP 1998

What is a Majorana nature of the surface states in our measurements?

Anomalous scattering of the Majorana fermions makes in Δ^* in the presence of disorder.

Δ^* is formed due to $\Psi=\Psi^\dagger$.

In the presence of the roughness, $p_{//}$ is no longer an eigenstate.

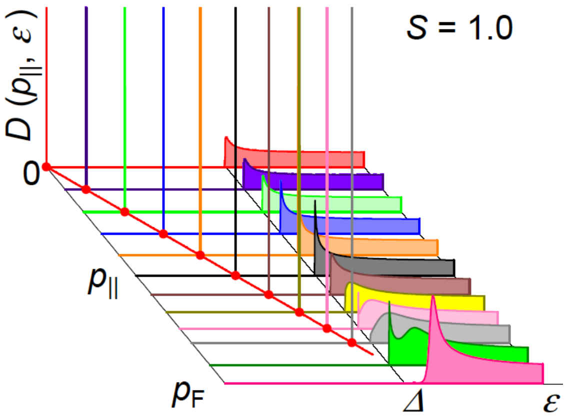
Scattering results in the broadening and energy shift.

Scattering between continuum above Δ and SABS results in strong label repulsion due to $\Psi=\Psi^\dagger$.

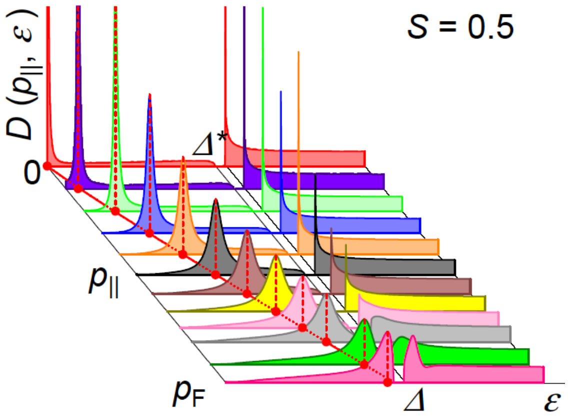
No states between Δ and Δ^*.

Majorana nature.

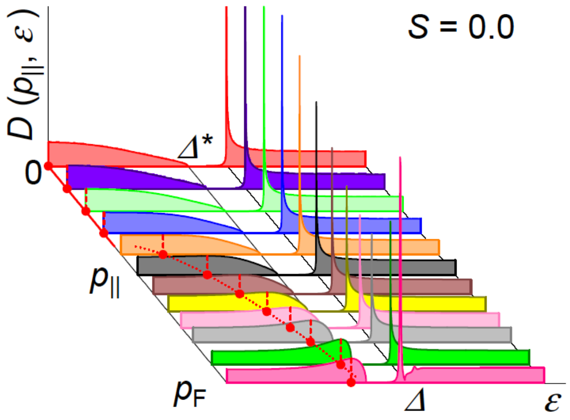
$$\epsilon - \epsilon_n^{(0)} = \sum_m \frac{|V_{nm}|^2}{\epsilon - \epsilon_m^{(0)}}$$



S = 1



S = 0.5



S = 0

Nagato *et al.*, JPSJ 2011

3. Challenges

Looking for the other topological natures.

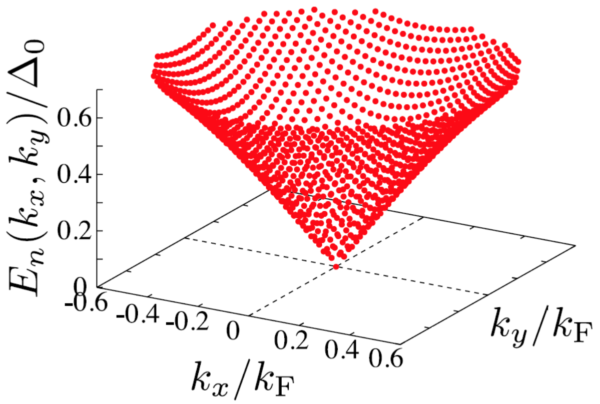
Topological phase transition,

Majorana Ising spin

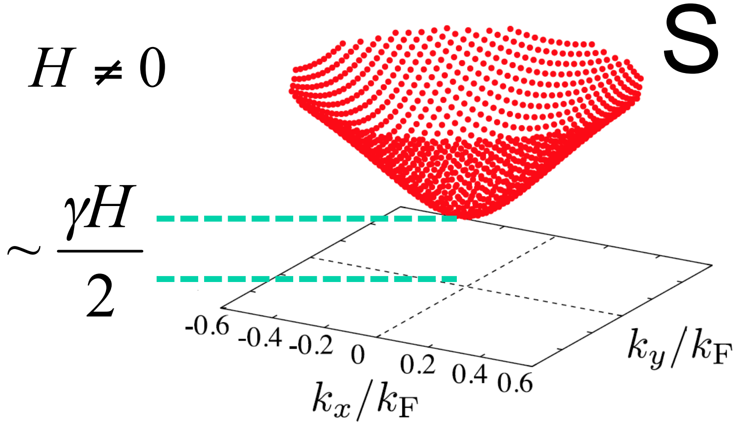
Magnetic field effect on Majorana states

S = 1

H = 0

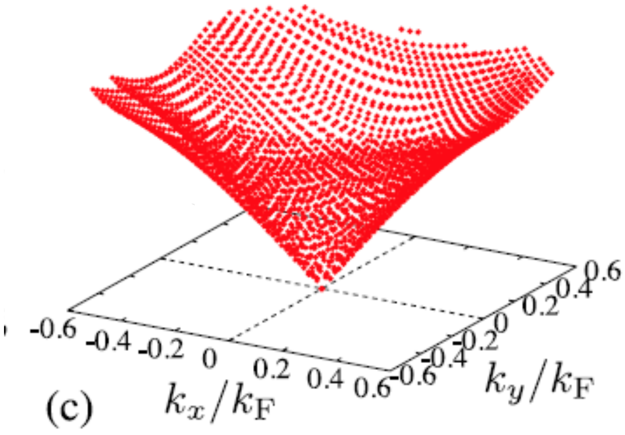


$H \neq 0$



Zero energy states are no longer topologically protected in perpendicular field.

$\boldsymbol{H} \perp \hat{z}$



Zero energy states do not response to parallel field.

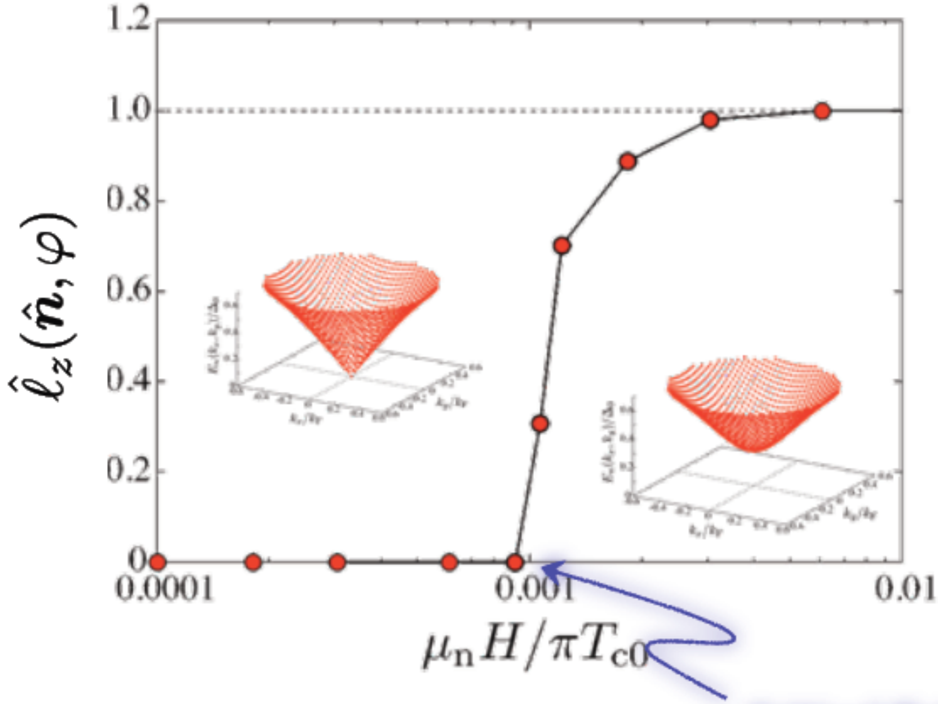
Majorana Ising spin.

Mizushima and Machida, JLTP 2011

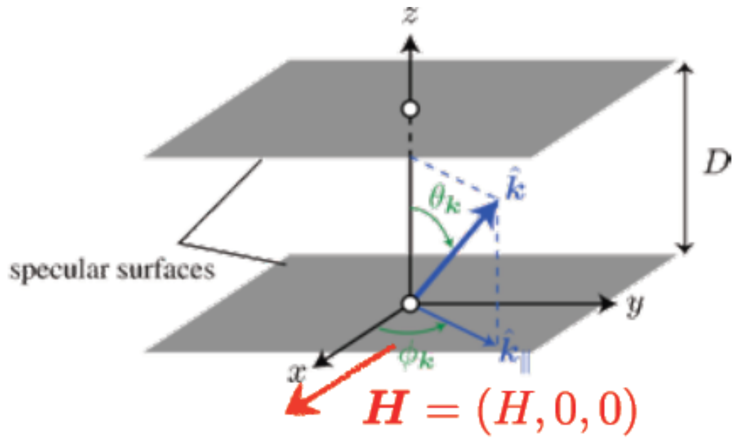
Chung and Zhang, PRL 2009

Parallel magnetic field effect

Field dependence of "l_z"



Critical field



c.f., dipolar field

$$H_{\rm D} \approx 30{\rm G} \approx 0.001\pi T_{\rm c0}/\mu_{\rm n}$$

$\hat{\ell}_z(\hat{\boldsymbol{n}},\varphi) = 0$

$\hat{\ell}_z(\hat{\boldsymbol{n}},\varphi) \neq 0$

$W = 2$

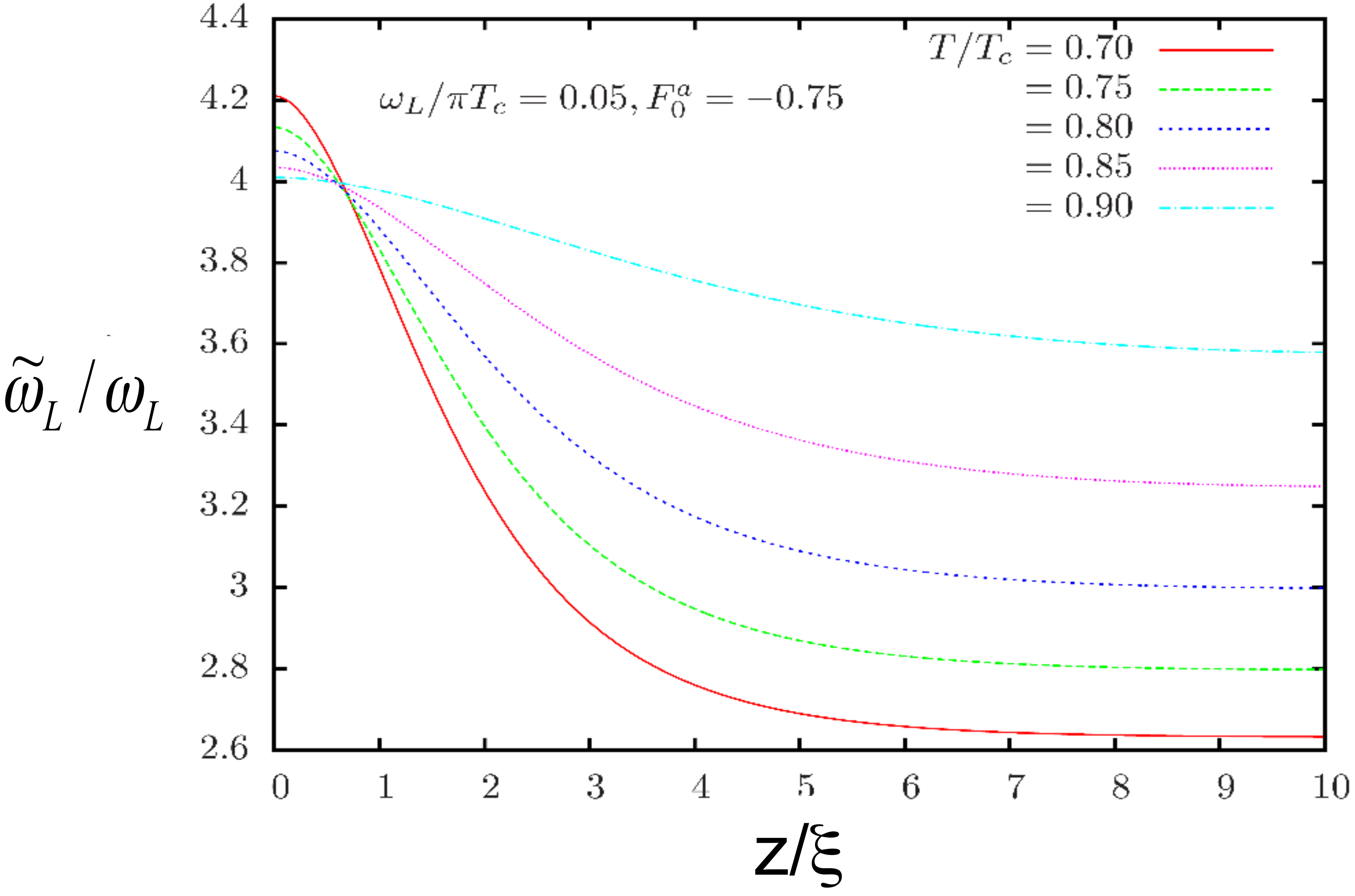
Symmetry protected topological phase

ill-defined W

Non-topological phase

Mizushima, Sato, Machida, PRL 2012

Enhanced effective magnetic field near a wall

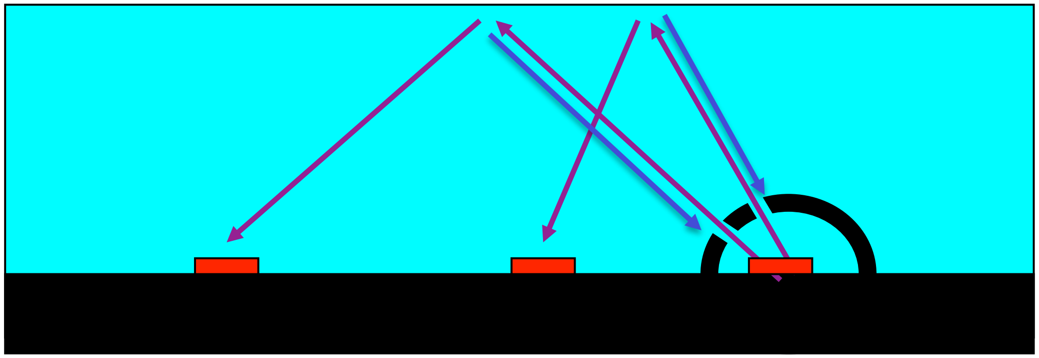


Nagato, Higashitani, Nagai, JPSJ, 78, 123603 (2009).

Angle resolved SDOS

Edge spin current

MEMS（Micro-Electro-Mechanical-System）



High spatial resolution will be useful to study angle dependence of reflection coefficients.

Angle dependence of reflection coefficients

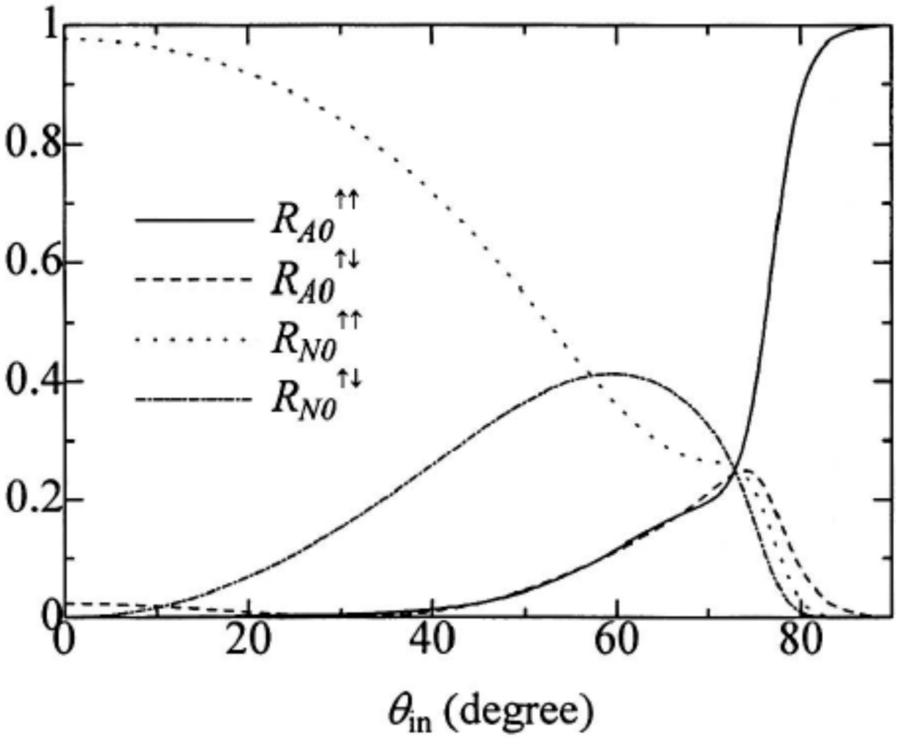


Fig. 17. Incident angle θ_{in} dependence of the Andreev and normal reflection coefficients when an quasi-particle with $\omega = 1.1\Delta_{\mathrm{bulk}}$ is injected toward the specular wall.

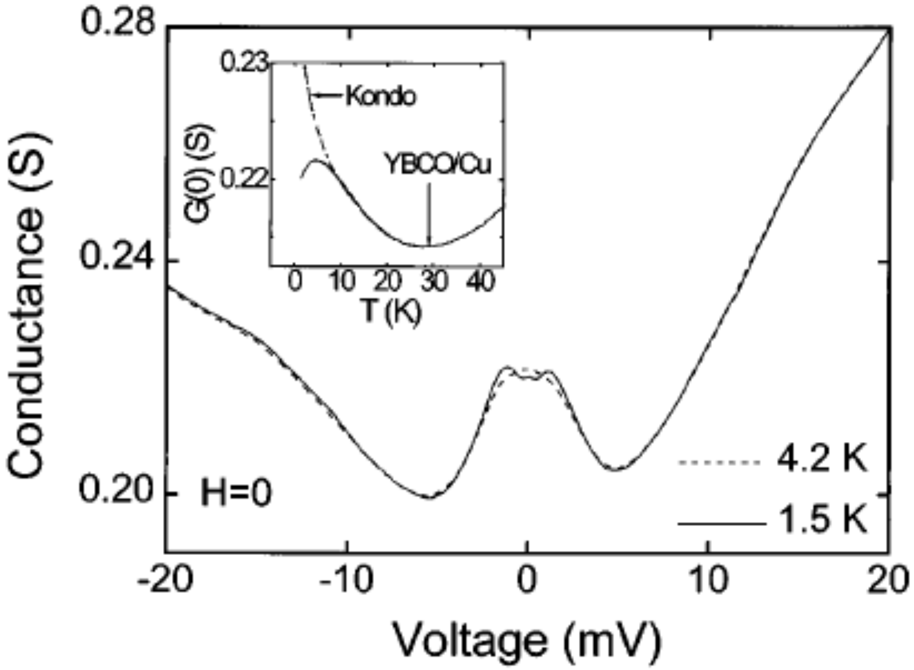
Nagato *et al*., JLTP 110, 1135 (1998)

How can we relate R(θ) to SDOS(θ)?

How can edge spin currents be detected?

Surface states transition by subdominant interaction at extremely low temperatures

Splitting of zero energy states in Cuprates



Transition of the surface Andreev bound states by s-wave interaction, d+is ???

Covington *et al*., PRL **79**, 277 (1997)

Fogelström, Rainer, and Sauls, PRL **79**, 281 (1997)
Matsumoto and Shiba, JPSJ **64**, 3384 (1995)

Impurity; Asano *et al*., PRB **69**, 214509 (2004)

Mixed symmetry surface superfluid

Subdominant f-wave interaction; $T_{cF} \sim 0.07T_c$

Northwestern Univ.
Nature Phys. (2008)
Nature 400 431 (1999)

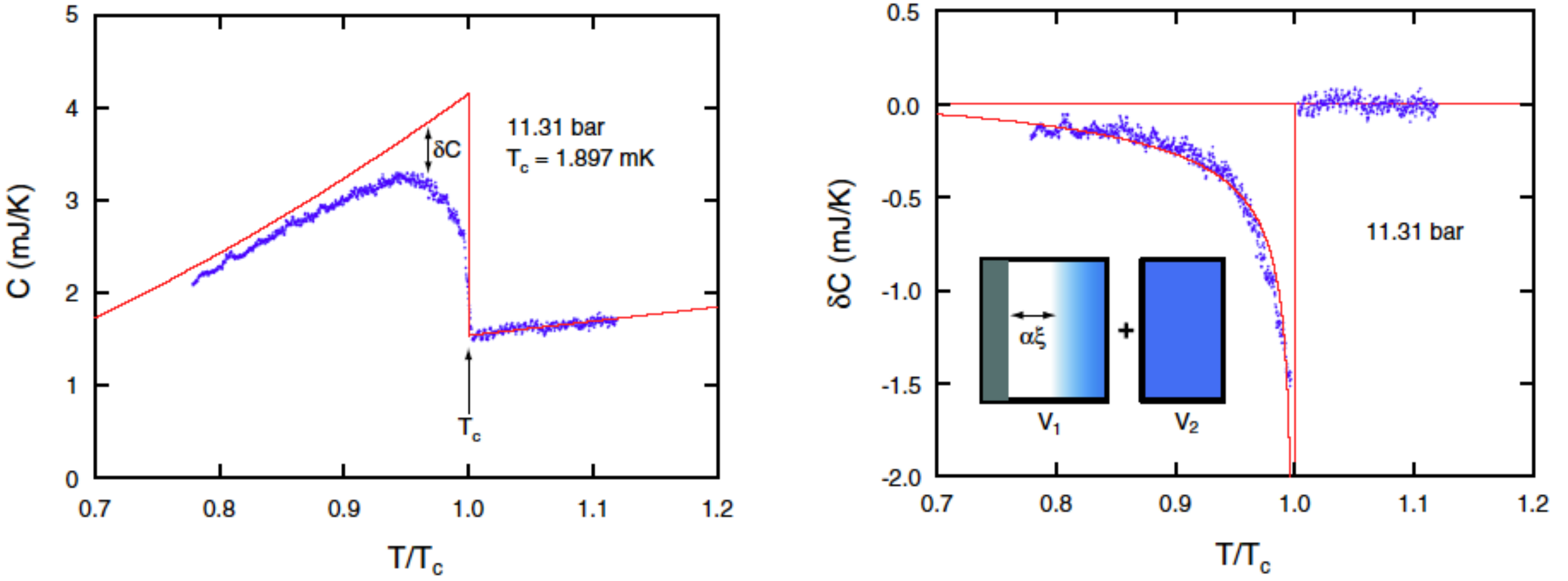
p + f surface superfluid

<100 μK?; technical challenge.

Other measurements detecting surface states

Surface specific heat

H. Choi, J. P. Davis, J. Pollanen, and W. P. Halperin,
Phys. Rev. Lett. **96**, 125301 (2006).



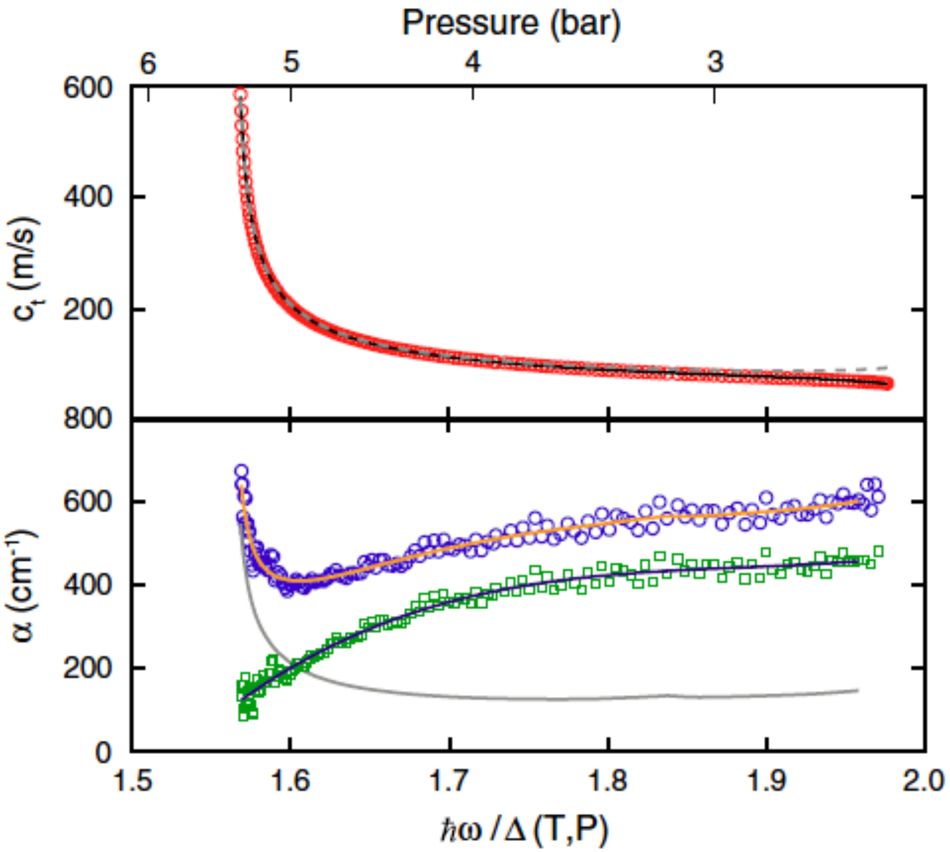
$$\delta C = (C - C_s)$$

$$C \quad = (V_1 + V_2)c_s + \alpha(T,P)\xi(T)A(c_n - c_s)$$

Ultralow temperature surface heat capacity measurements are also needed.

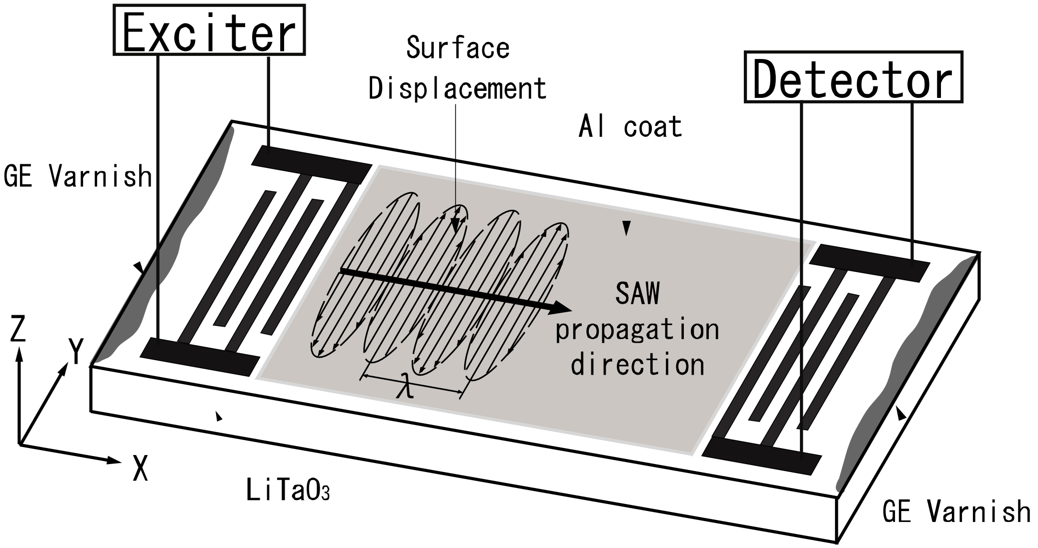
Damping of the transverse zero sound

J. P. Davis, J. Pollanen, H. Choi, J. A. Sauls, W. P. Halperin, and
A. B. Vorontsov, Phys. Rev. Lett. **101**, 085301 (2008).



Extra damping of transverse sound is probably due to SABS.

Surface acoustic wave (SAW) sensors; Rayleigh-SAW or shear horizontal (SH)-SAW



This sensor provides the same information of Z as the quartz transducers do and is also suitable for a slab geometry.

New type of acoustic sensor for ^{3}He in the slab.

⬇

Can be used to look for new phases as stripe phase acoustically.

Aoki *et al.*, J. Low Temp. Phys. **134**, 945 (2004)
Y. Okuda and R. Nomura, J. Phys.: Cond. Matt. **24**, 343201 (2012)

Summary

Achievements

Surface Majorana states of ^{3}He-B has been detected by acoustic impedance measurements.

Boundary condition dependence of SDOS, topological stability of the surface zero modes, anomalous scattering of Majorana fermions in the presence of disorder

……

Challenges

Topological phase transitions, Majorana Ising spin, enhanced surface magnetic susceptibility, angle resolved SDOS, edge spin and mass currents, transition of the surface states by f-wave interaction at extremely low temperatures, stripe phase in a slab

….

Review; Y. Okuda and R. Nomura, J. Phys.: Cond. Matt. **24**, 343201 (2012)