Topological superfluid ^{3}He under mesoscopic confinement

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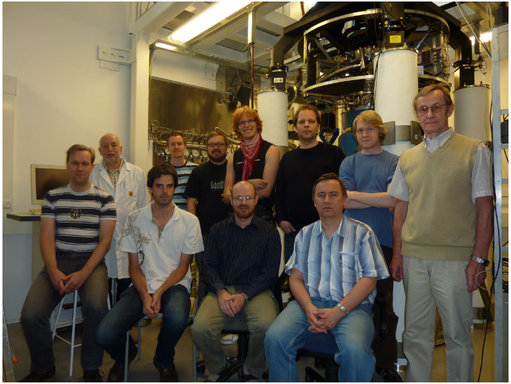
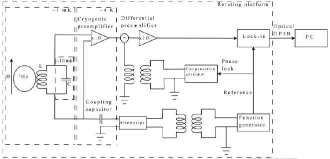
M. Krusius anniversary symposium
04/11/2022

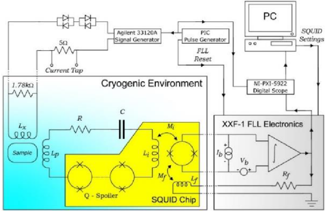
Prelude



Then:
Cryogenic GaAs MESFET preamp
Sample size ~ cm^3

Now:
Two-stage DC SQUID amplifier
Sample size ~ 10 μm^3

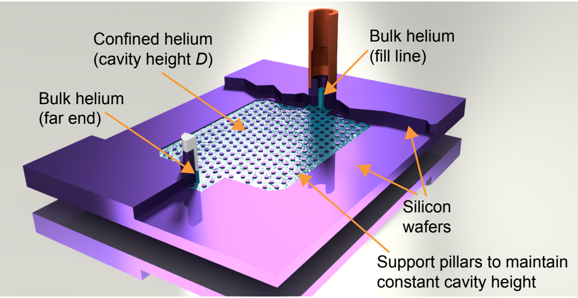




Outline

1. Introduction to superfluid ^{3}He
   - Effect of confinement on phase stability
   - Tuning the boundary condition for scattering of quasiparticles
2. Details of experimental setup
   - Nanofabricated atomically smooth cavities
   - $D \sim \xi_0$: Bulk properties eliminated; surface effects dominate
3. Summary of main results so far
   - Chiral superfluidity in quasi-2D limit
   - Magnetic spin-flip scattering
   - Spatially modulated phase
4. Future prospects
   - Early universe phase transitions
   - Low-field NMR
   - Thermal transport
   - Size quantization

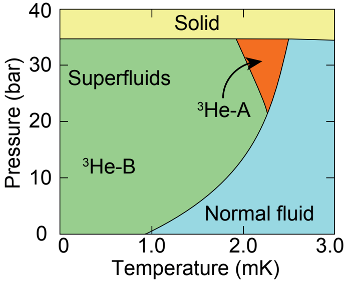
Type of confinement in this work:



- Allows to characterize surface pair breaking in the absence of defect and impurity scattering.

Phases of superfluid ^{3}He in bulk

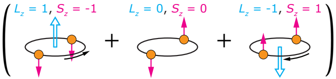
- Firmly established unconventional spin-triplet p-wave superfluid with $S = L = 1$.
  - Spin-$\frac{1}{2}$ particle: good for NMR.
- Extremely pure sample at the lowest temperatures; even ^{4}He impurities “frozen” on the sample walls.
- Due to Cooper pairs’ internal structure, multiple stable superfluid phases exist.



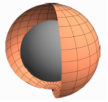
- ^{3}He-B, pseudo-isotropic: long-range order in relative orientation of $\hat{\mathbf{l}}$ and $\hat{\mathbf{s}}$:

$$A_{\mu j} = e^{i\phi}\Delta R_{\mu j}(\hat{\mathbf{n}}, \theta);$$

$\Psi = e^{i\phi}\Delta$



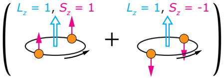
$, L_z = -S_z$

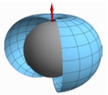


- ^{3}He-A, anisotropic: long-range order in vector $\hat{\mathbf{d}} \perp \hat{\mathbf{s}}$ and in $\hat{\mathbf{l}} = \hat{\mathbf{m}} \times \hat{\mathbf{n}}$:

$$A_{\mu j} = e^{i\phi}\Delta \hat{d}_{\mu}\left(\hat{m}_j + i\hat{n}_j\right);$$

$\Psi = e^{i\phi}\Delta$

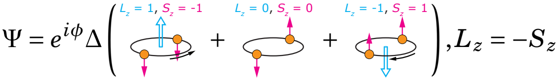


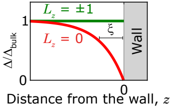


[Gap illustrations by J. Sauls]

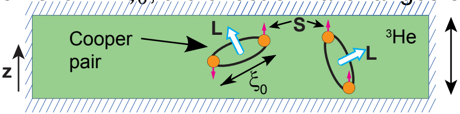
Phase suppression under confinement

- In bulk at low pressures, time-reversal invariant ^{3}He-B is the stable phase.
- Anisotropy at the walls, where the preferred orientation is $\hat{\mathbf{l}} \parallel \hat{\mathbf{z}}$; only $L_z \pm 1$ pairs exist.



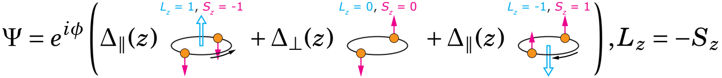


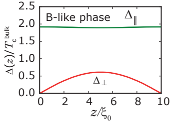
- In strong confinement $D \sim \xi_0$, the effect of walls ranges over the whole sample: $\Delta \equiv \Delta(z)$.



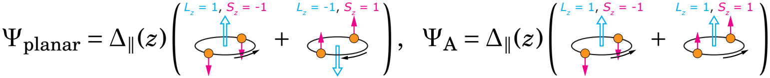
$D \sim \xi_0(P)$ = 20 - 80 nm

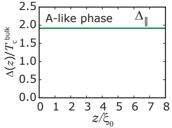
- B-phase gradually develops planar distortion as D decreases:



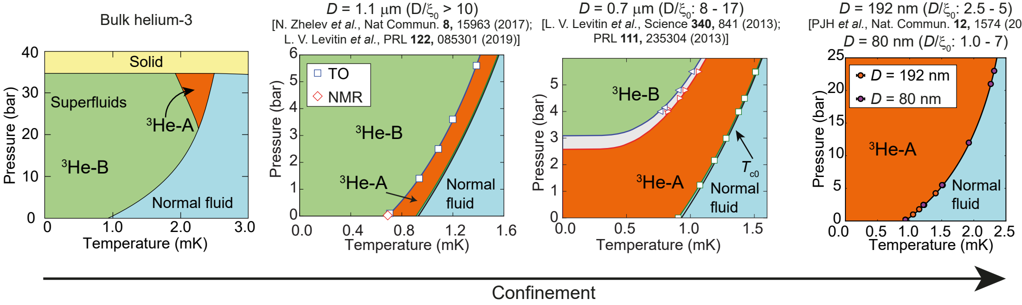


- Finally, confinement $D \lesssim 10\xi_0$ forces $\Delta_\perp(z) = 0$. [A. B. Vorontsov and J. A. Sauls, PRB **68**, 064508 (2003)]





Phase-diagram modification



Bulk helium-3

D = 1.1 μm ($D/\xi_0 > 10$)
[N. Zhelev *et al.*, Nat Commun. **8,** 15963 (2017); L. V. Levitin *et al.*, PRL **122,** 085301 (2019)]

D = 0.7 μm (D/ξ_0: 8 - 17)
[L. V. Levitin *et al.*, Science **340,** 841 (2013); PRL **111,** 235304 (2013)]

D = 192 nm (D/ξ_0: 2.5 - 5)
[PJH *et al.*, Nat. Commun. **12,** 1574 (2021)]
D = 80 nm (D/ξ_0: 1.0 - 7)

Confinement

Quasiparticle scattering boundary condition

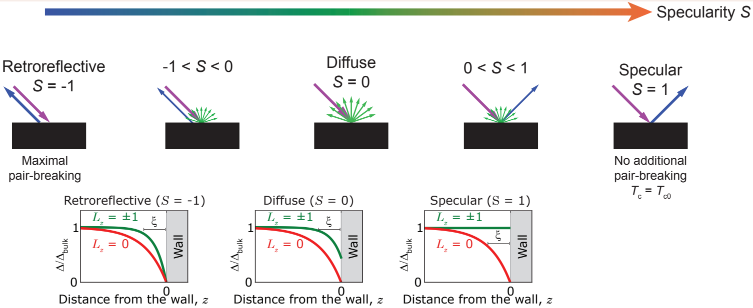
Theory

- Any roughness at the surface results in suppression of gap and T_c in confined p-wave systems.

  [V. Ambegaokar *et al.*, PRA **9**, 2676 (1974); L. H. Kjäldman *et al.*, JLTP **33**, 577 (1978); A. B. Vorontsov and J. A. Sauls, PRB **68**, 064508 (2003)]

- For purely momentum scattering of quasiparticles, boundary condition is characterised by specularity S.

  [Y. Nagato *et al.*, JLTP **110**, 1135 (1998); A. B. Vorontsov, Phil. Trans. R. Soc. A **376**, 20150144 (2018)]

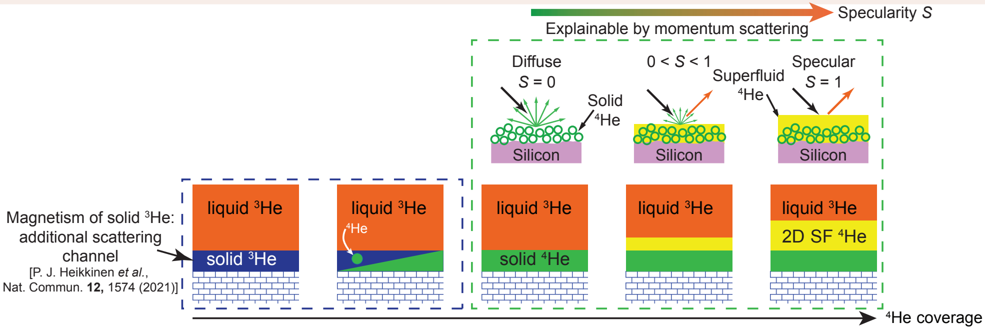


Quasiparticle scattering boundary condition

Experiments

- Pure ^{3}He in the slab forms magnetically ordered layer of “solid” ^{3}He. [A. I. Ahonen *et. al*, J. Phys. C. **9**, 1665 (1976)]
- Preplating with heavier ^{4}He replaces ^{3}He atoms on the surface.
  - Tunes scattering towards specular. [D. A. Ritchie *et al.*, PRL **59**, 465 (1987); M. R. Freeman and R. C. Richardson, PRB **41**, 11011 (1990)]
- Onset of specularity coincides with superfluid transition of ^{4}He film.

[D. McQueeney *et al.*, PRL **52**, 1325 (1984); S. M. Tholen and J. M. Parpia, PRL **67**, 334 (1991)]



Magnetism of solid ^{3}He: additional scattering channel
[P. J. Heikkinen *et al.*, Nat. Commun. **12,** 1574 (2021)]

Summary of order-parameter modification under confinement

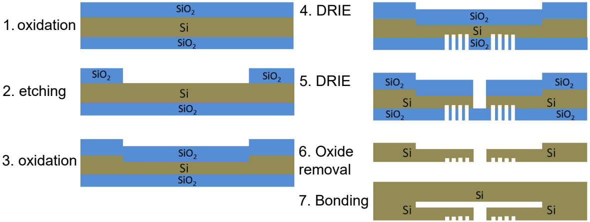
1. Confinement favours A-like phase via anisotropic surface pair breaking
   - Determines which phase is the stable phase
   - Effective confinement D/ξ_0 tuneable by pressure

2. Quasiparticle scattering boundary condition can suppress all order-parameter components
   - Determines the superfluid transition temperature T_c
   - Tuneable by ^{4}He concentration

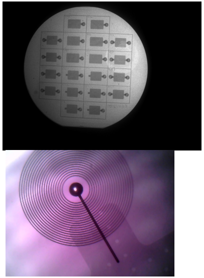
Nanofabrication

Standard silicon nanofabrication techniques

[N. Zhelev *et al.*, Rev. Sci. Inst. **89,** 073902 (2018);
S. Dimov *et al.*, Rev. Sci. Inst. **81,** 013907 (2010)]

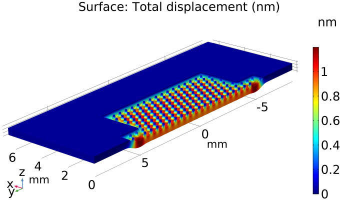


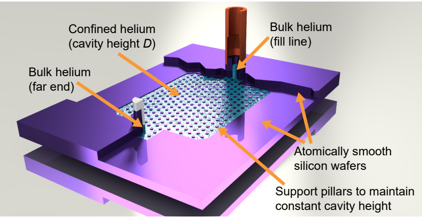
Infrared imaging to detect defects

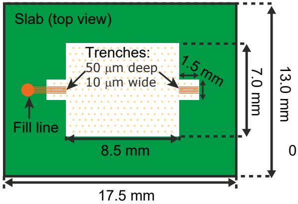


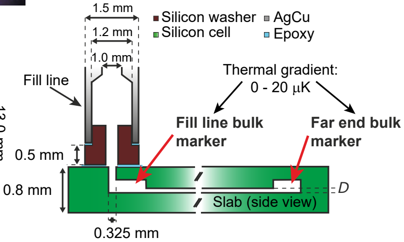
FEM modelling for cavity distortion:

⌀100 μm pillars; 1.0 nm/bar
⌀200 μm pillars; 2.6 nm/bar

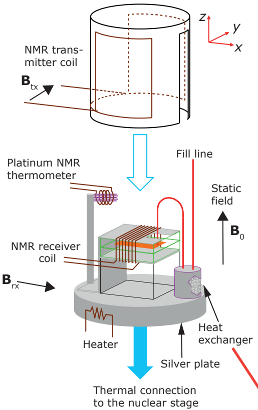








NMR setup

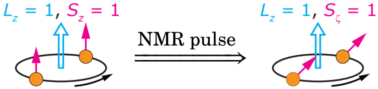


Orange: slab of helium
Green: two silicon wafers
Black: Macor cell holder
Grey: Silver foils

- SQUID-NMR experiments with Larmor frequency ~ 1 MHz ($B_0 = 32\,\mathrm{mT}$).

[L. V. Levitin *et al.*, App. Phys. Lett. **91**, 262507 (2007); SQUIDs from PTB, Berlin: D. Drung *et al.*, IEEE Trans. Appl. Supercond. **17**, 699 (2007)]

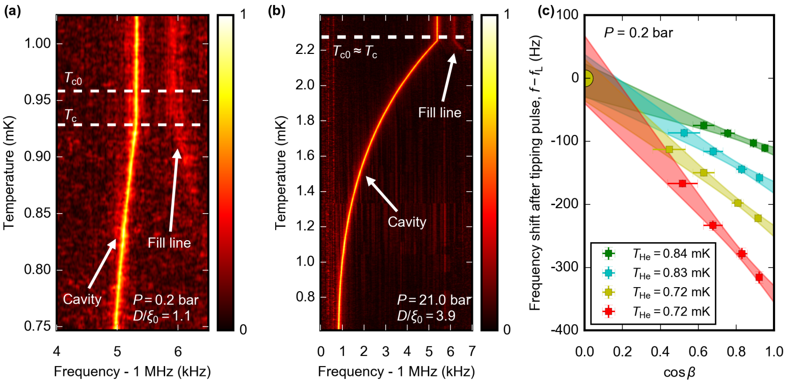
- NMR pulse tips the spin of the Cooper pairs by an angle β:



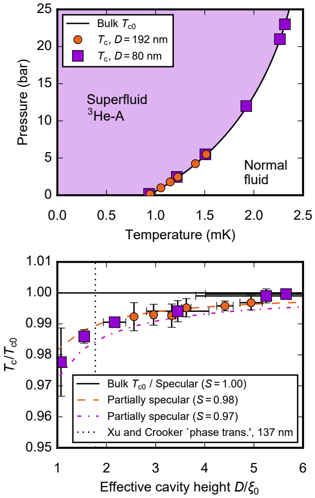
- As $\mathbf{S}$ rotates relative to $\mathbf{L}$, the dipolar interaction (torque) results in NMR frequency shift $f^2 - f_\mathrm{L}^2 \propto \langle \Delta^2(z) \rangle$.
  - In a slab where $D \ll \xi_\mathrm{D} \approx 10\,\mu$m, uniform precession determined by spatially averaged gap $\langle \Delta^2(z) \rangle$.
  - Frequency shift characteristic for each superfluid phase.
    - Either negative or positive, depending on whether the pre-tipping state is in (local) maximum or minimum of spin-orbit energy, respectively.
    - Configuration $\mathbf{S}, \mathbf{H}, \mathbf{L} \parallel \hat{\mathbf{z}}$: ^{3}He-A negative Δf, ^{3}He-B positive Δf.

Chiral superfluidity in quasi-2D limit

- 80 nm high cavity, superfluid ^{4}He boundary condition (6+ layers).
- Equal-spin-pairing state, negative $\Delta f \propto -\cos\beta$.



- Almost fully unsuppressed $T_c \approx T_{c0}$.

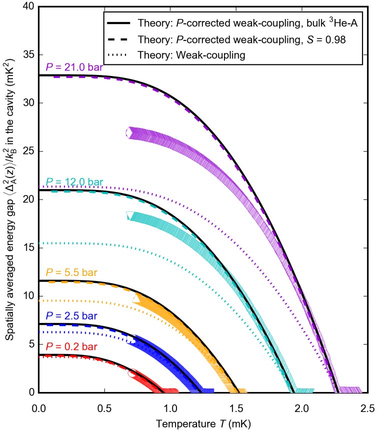


- Quasiclassical calculations provide T_c vs. specularity S.
- Results consistent with ^{3}He-A being stable down to $D/\xi_0 \approx 1$.

Measurement of strong-coupling over full pressure range

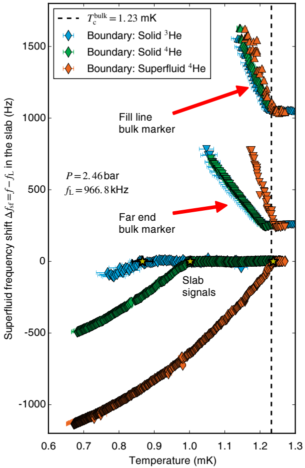
- A-phase frequency shift in a slab (for small $\beta \sim 1^\circ$): $|f^2 - f_{\mathrm{L}}^2| = \zeta(P)\langle\Delta_{\mathrm{A}}^2(z)\rangle$.
- Near T_{c}, $\langle\Delta_{\mathrm{A}}^2(z)\rangle \propto (1 - T/T_{\mathrm{c}})$.
- Universal scaling, using initial slopes, between calculated $\langle\Delta_{\mathrm{A}}^2(z)\rangle$ and measured Δf.

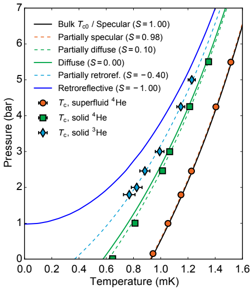
- No strong-coupling calculations of bulk Δ_{A} over full $P - T$ plane exist.
  - Strong-coupling quasiclassical theory shows excellent results for bulk AB transition line and specific heat. [J. J. Wiman, PhD Thesis, Northwestern University (2019)]



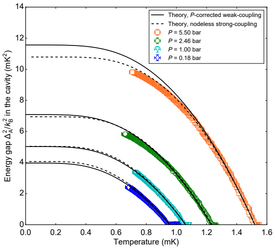
Boundary condition tuning, $D = 200\,\mathrm{nm}$

- Three boundary conditions, each resulting in different transition temperature T_c in the cavity.



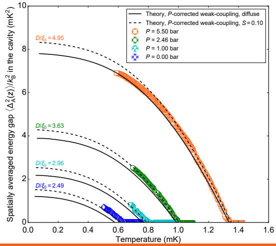


Superfluid ^{4}He boundary



- Almost perfectly specular and close to diffuse boundary conditions created.
- Solid ^{3}He introduces additional suppression of T_c unexplainable by geometrical differences.
- Magnetic properties must be taken into account!
- Will be further studied as a function of $\mathbf{H}$.

Solid ^{4}He boundary

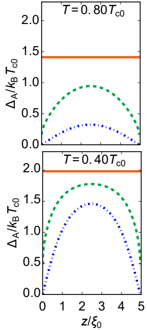


Spin-flip exchange scattering

- Non-topological surface-bound states (Andreev bound states) in ^{3}He-A:
  - The less specular the surface the higher the density of states at zero energy.

  ⇒ Specularity connects T_c suppression, gap suppression, and surface DOS.
- Pair breaking beyond diffuse indicates increased density of low-energy bound states.
- Three possible mechanisms generating an excess of low-energy bound states.
  - Backscattering and suppressive scattering from static magnetised boundary not compatible.
  - Plausible mechanism: magnetic exchange scattering. Allows spin-flip processes. Requires $S \neq 0$.

[PJH *et al.*, Nat. Commun. **12,** 1574 (2021)]

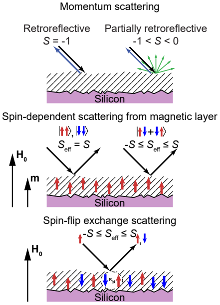


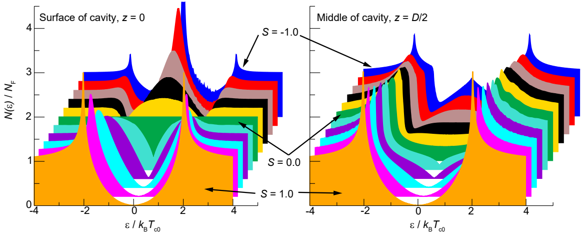
Energy of SBS:

$$\frac{E_{\mathrm{SBS}}}{\Delta} = \pm \cos\frac{\phi}{2}$$

ϕ is the scattering angle; *x-y* plane rotation in momentum space for skew scattering in ^{3}He-A.

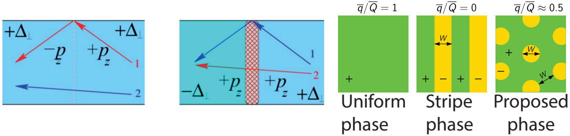
[A. B. Vorontsov, Phil. Trans. R. Soc. A **376,** 20150144 (2018)]





Spatially modulated order parameter

- A-phase states $\mathbf{l} \parallel \hat{\mathbf{z}}$ and $\mathbf{l} \parallel -\hat{\mathbf{z}}$ degenerate.
- Coexistence of two B-phase spin-orbit orientations (stable and metastable) separated by textural (soft) domain wall possible.
  - Existence of B_- follows from combination of $H > H_\mathrm{D}$ and confinement.
- Pair density wave: Spatial modulation of confined B-phase, i.e., spontaneously formed hard domain walls where $\Delta_\perp$ changes sign.

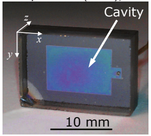


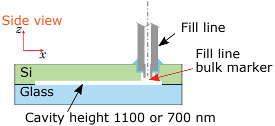
- Domains reduce surface pair breaking.
- Experiment points towards 2D PDW.

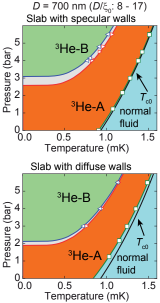
Theory:
Stripe phase: A. B. Vorontsov and J. A. Sauls, PRL **98,** 045301 (2007);

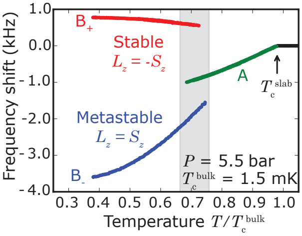
Recent work on 2D PDW: T. Mizushima *et al.*

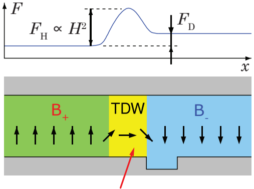
First generation Si-Glass cavities
[L. V. Levitin *et al.*, Science **340,** 841 (2013); PRL **111,** 235304 (2013), PRL **122,** 085301 (2019)]





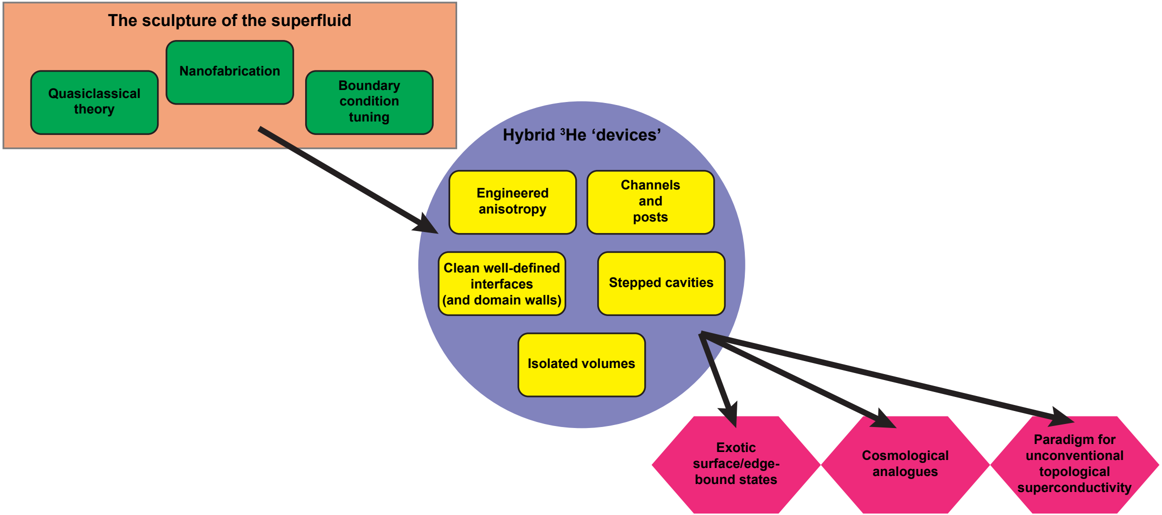






Textural domain wall

Building blocks for future



The sculpture of the superfluid

Quasiclassical theory

Nanofabrication

Boundary condition tuning

Hybrid ^{3}He 'devices'

Engineered anisotropy

Channels and posts

Clean well-defined interfaces (and domain walls)

Stepped cavities

Isolated volumes

Exotic surface/edge-bound states

Cosmological analogues

Paradigm for unconventional topological superconductivity

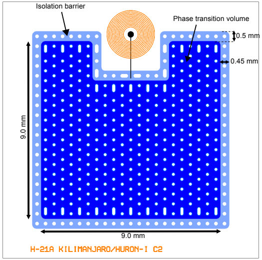
A-B transition under confinement

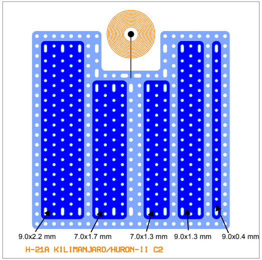
- Mechanism for the first-order phase transition between ^{3}He-A and ^{3}He-B is still unresolved.
  - External (cosmic rays or boundary effects), or intrinsic (resonant tunnelling, intermediate state)?
- Laboratory-based analogue to early-universe phase transitions.
  - Homogeneous nucleation theory predicts lifetime of supercooled A phase ∼ age of the universe.
  - Phase boundary propagation ⇒ gravitational wave production.

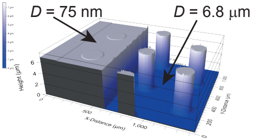
QUEST DMC

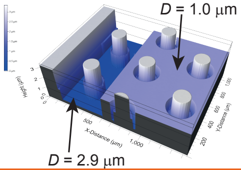
Quantum Enhanced
Superfluid Technologies for
Dark Matter and Cosmology

- Isolated volumes with atomically smooth boundaries allow tuning between normal, B, and A phases by pressure.
- A-to-B transition on cooling within the deep “lakes”.
- B-to-A transition on warming on top of the “mountains”.



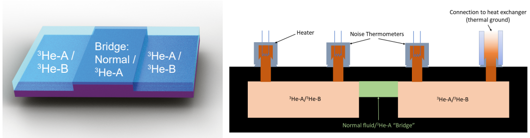




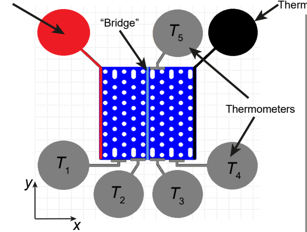


Thermal transport in confined volumes

Illustration of multi-height design



Photomask used in nanofabrication



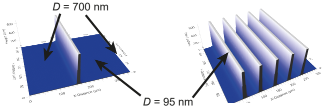
Various thermal transport measurements in single design:

T_1 to T_2 and T_3 to T_4
κ_{xx} across the cavity

T_2 to T_3
κ across interfaces

T_3 to T_5
thermal Hall conductivity κ_{xy}

Optical profilometry after fabrication



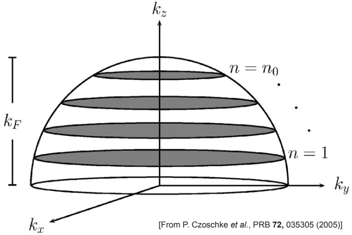
- Stepped confinement to create one or several bridges
  $\Rightarrow$ clean S-N-S or ^{3}He-B to ^{3}He-A interfaces
  - Flexibility of fabrication allows for more complex designs.
- Anomalous thermal response in 1.1 µm high channel. [D. Lotnyk *et al.*, Nat. Commun. **11,** 4843 (2021)]
  - Role of surface and edge excitations?
- Anomalous thermal Hall effect in ^{3}He-A.

  [P. Sharma *et al.*, arXiv:2209.04004 [cond-mat.supr-con] (2022)]
  - Requires specularity $S < 1$.
  - Would confirm chirality and the nature of surface scattering.
- Multiprobing with local sensitive thermometers.
  - Miniaturised current-sensing noise thermometers will be prototyped first.

    [A. Casey *et al.*, JLTP **175,** 764 (2014)]

Size quantization and gapped chiral superfluidity

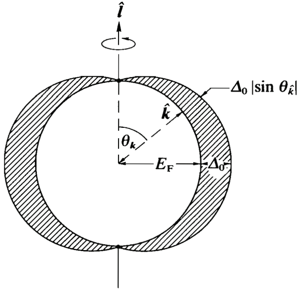
- Purely 2-dimensional ^{3}He-A is fully gapped: no nodes in the Fermi surface.
  - Dimensional quantization under confinement results in a set of allowed substates of k_z below k_F.



[From P. Czoschke *et al.*, PRB **72**, 035305 (2005)]

- Allowed values: $k_z = \frac{\pi n}{D}$
- $\Delta_\mathrm{A} = \Delta_0 \sin\theta; \quad k_\mathrm{F}(P=0) = 7.9\,\mathrm{nm}^{-1}$
- $\sin\theta = \left(1 - \frac{k_z^2}{k_\mathrm{F}^2}\right)^{1/2}$
- Assume $k_z(n_0) = k_\mathrm{F} : n_0 = \frac{k_\mathrm{F} D}{\pi}$

  $\Rightarrow \Delta_\mathrm{A}(n) = \Delta_0 \left(1 - \frac{n^2}{n_0^2}\right)^{1/2}$

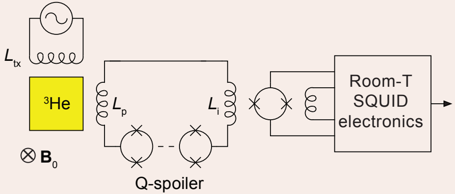


[From D. Vollhardt and P. Wölfle, *The Superfluid Phases of Helium 3* (1990)]

- $n = n_0 - 1 \Rightarrow \Delta_\mathrm{A}(n) = \Delta_0 \left(\frac{2}{n_0} - \frac{1}{n_0^2}\right)^{1/2}.$
  - $D = 40\,\mathrm{nm} \Rightarrow n_0 \approx 100$ and $\min(\Delta_\mathrm{A}) \approx 0.14\Delta_0$. $D = 10\,\mathrm{nm} \Rightarrow n_0 \approx 25$ and $\min(\Delta_\mathrm{A}) \approx 0.28\Delta_0$.
- If D and P chosen so that $k_z(n_0) \neq k_\mathrm{F}$, **fully gapped chiral superfluid** with gap $\min(\Delta_\mathrm{A})$
  - Access to chiral Majorana edge states and ground-state edge currents? [J. A. Sauls, PRB **84,** 214509 (2011)]
  - Edge-induced quantum Hall effect? [G. E. Volovik, JETP Lett. **55,** 368 (1992)]

NMR at low magnetic fields

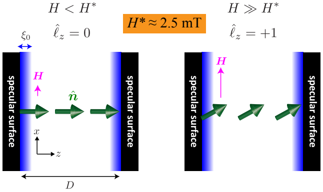
Broadband NMR



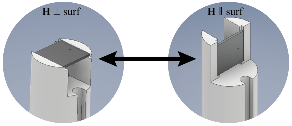
- C. P. Lusher *et al.*, Appl. Supercond. **6,** 591 (1998)
- Superconducting flux transformer.
- No f_0, freedom to tune B_0.
- Better signal-to-noise ratio than tuned setup below $f_0 \sim 100\,\mathrm{kHz}$.
- First will be used to study solid ^{3}He boundary condition at lower fields.

- Topological phase transition in ^{3}He-B at $H = H^* \approx 2.5\,\mathrm{mT} \sim 100\,\mathrm{kHz}$ for $\mathbf{H} \perp \hat{\mathbf{z}}$.
- Massless surface states (Majorana fermions) acquire mass.
- Anomalous enhancement of the surface spin susceptibility at $H = H^*$ arises from odd-frequency even-parity pairing of the surface states, as parametrised by topological order $\hat{l}_z$:

$$\chi_{\mathrm{surf}} = \chi_{\mathrm{N}} + \sqrt{1-\hat{l}_z^2}\,\chi^{\mathrm{OP}} + \hat{l}_z\,\chi^{\mathrm{EP}}$$

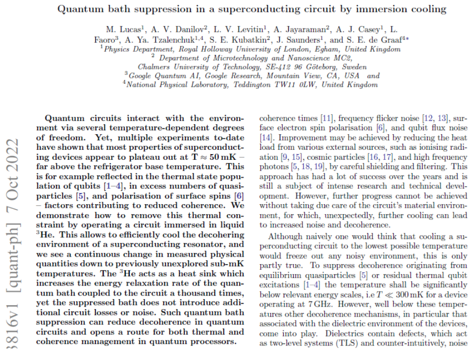


[T. Mizushima *et al.*, J. Phys.: Condens. Matter **27,** 113203 (2015)]



Helium-3 helping to cool down quantum circuits

- Immersing quantum device to liquid helium-3 allows it to cool down to previously unexplored sub-mK temperatures. [M. Lucas *et al.*, arXiv:2210.03816 [quant-ph] (2022)]
  - The decohering environment cools down via ^{3}He acting as a heat sink.
  - Relaxation rate of bath of two-level systems dramatically increases.
  - A promising way to understand and suppress noise and decoherence in quantum circuits in the future.



Quantum bath suppression in a superconducting circuit by immersion cooling

M. Lucas[1], A. V. Danilov[2], L. V. Levitin[1], A. Jayaraman[2], A. J. Casey[1], L. Faoro[3], A. Ya. Tzalenchuk[1,4], S. E. Kubatkin[2], J. Saunders[1], and S. E. de Graaf[4*]

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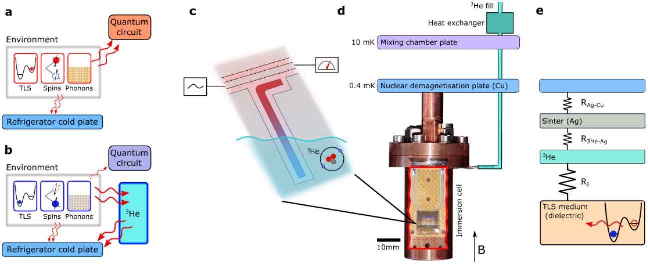
Quantum circuits interact with the environment via several temperature-dependent degrees of freedom. Yet, multiple experiments to-date have shown that most properties of superconducting devices appear to plateau out at T ≈ 50 mK – far above the refrigerator base temperature. This is for example reflected in the thermal state population of qubits [1–4], in excess numbers of quasiparticles [5], and polarisation of surface spins [6] – factors contributing to reduced coherence. We demonstrate how to remove this thermal constraint by operating a circuit immersed in liquid ^{3}He. This allows to efficiently cool the decohering environment of a superconducting resonator, and we see a continuous change in measured physical quantities down to previously unexplored sub-mK temperatures. The ^{3}He acts as a heat sink which increases the energy relaxation rate of the quantum bath coupled to the circuit a thousand times, yet the suppressed bath does not introduce additional circuit losses or noise. Such quantum bath suppression can reduce decoherence in quantum circuits and opens a route for both thermal and coherence management in quantum processors.

coherence times [11], frequency flicker noise [12, 13], surface electron spin polarisation [6], and qubit flux noise [14]. Improvement may be achieved by reducing the heat load from various external sources, such as ionising radiation [9, 15], cosmic particles [16, 17], and high frequency photons [5, 18, 19], by careful shielding and filtering. This approach has had a lot of success over the years and is still a subject of intense research and technical development. However, further progress cannot be achieved without taking due care of the circuit's material environment, for which, unexpectedly, further cooling can lead to increased noise and decoherence.

Although naively one would think that cooling a superconducting circuit to the lowest possible temperature would freeze out any noisy environment, this is only partly true. To suppress decoherence originating from equilibrium quasiparticles [5] or residual thermal qubit excitations [1–4] the temperature shall be significantly below relevant energy scales, i.e $T \ll 300\,\mathrm{mK}$ for a device operating at 7 GHz. However, well below these temperatures other decoherence mechanisms, in particular that associated with the dielectric environment of the devices, come into play. Dielectrics contain defects, which act as two-level systems (TLS) and counter-intuitively, noise



Current results

- Superfluid ^{3}He order parameter can be modified by combination of mesoscopic confinement and quasiparticle scattering boundary condition, and measured by SQUID-NMR.
- $D = 80\,$nm: Chiral ^{3}He-A survives down to quasi-2D limit $D/\xi_0 \approx 1$.
- $D = 200\,$nm: Magnetically active solid ^{3}He boundary layer results in additional, unexpected, suppression of superfluid transition temperature.
- $D = 1100\,$nm: Evidence for 2D spatially modulated phase.

Future directions

- Studies in even thinner cavities to gain access to chiral Majorana states at the edges.
- Studies at lower magnetic fields.
- Fabrication of hybrid nanofluidic structures by varying cavity height and by adding islands in the middle of the slab to expand studies of topological mesoscopic superfluidity.
  - Well-defined interfaces and phase boundaries.
  - Thermal and spin transport. Hall effects.
  - Phase nucleation: cosmological relevance.
  - Control of domain walls, surface and edge states. Surface and edge currents.