

WP2: Early-Universe phase transitions in superfluid ^3He : progress and future

Petri J. Heikkinen ¹

¹Department of Physics, Royal Holloway, University of London
Egham, UK



QUEST-DMC meeting, Liverpool
17/10/2025





■ Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

Funded by UKRI Quantum Technologies for Fundamental Physics programme

- 1 Detection of sub-GeV dark matter with a quantum-amplified superfluid ^3He calorimeter.

- What is the nature of dark matter?

- 2 **Phase transitions in extreme matter.**

- How did the early Universe evolve?

- Linked through requirement of beyond Standard Model physics and the internationally unique experimental approach of combining quantum sensors with ^3He at ultralow temperatures.



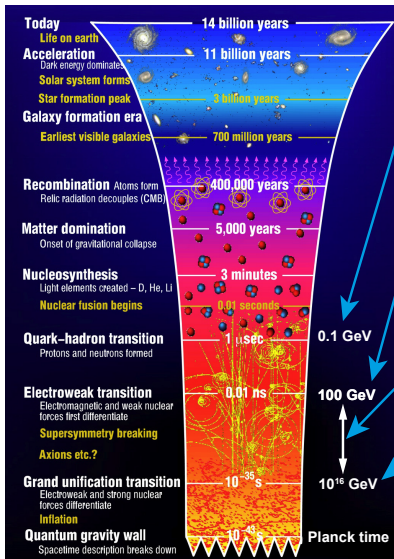
Engineering and
Physical Sciences
Research Council



Science and
Technology
Facilities Council

- 1 Phase transitions in ^3He and in cosmology.
- 2 A-to-B phase nucleation puzzle in superfluid ^3He .
 - Role of various internal and external mechanisms.
 - Kibble-Zurek mechanism and its simulation.
- 3 Details of experimental SQUID-NMR setup.
 - Nanofabricated atomically smooth silicon cell.
 - Multiple tiny isolated phase-transition volumes.
 - Making use of confinement and quasiparticle scattering boundary condition.
 - Particle interaction simulations inside the cryostat.
- 4 Results
 - No catastrophe line.
 - Strong supercooling and superheating observed.
 - Stochastic nature of observed phase transitions, such as triggered by radiation.
 - Thermal quenches of the large enough normal-state bubbles into the A or B phase.
 - Non-monotonic T and P dependence of lifetime of supercooled $^3\text{He-A}$.
- 5 Conclusions and future.

The cosmological phase transitions



QCD phase transition
Within SM: crossover

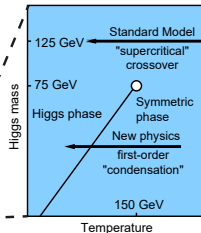
EW phase transition
Within SM: cross-over
Beyond SM: 1st order.
Baryogenesis?

Peccei-Quinn phase transition
Before, during, or after Inflation
10³ - 10¹⁴ GeV
Beyond SM: 1st or 2nd order.
Could solve the strong CP problem;
gives rise to an axion (a viable Dark Matter candidate).
[L.D. Rose *et al.*, JHEP **04**, 25 (2020)]

GUT phase transition
Beyond SM: 1st or 2nd order.
Role in the Inflation?
Baryogenesis?

[Image adapted from The Stephen Hawking
Centre for Theoretical Cosmology:

https://www.ctc.cam.ac.uk/outreach/origins/big_bang_three.php



Consequences from various beyond-Standard Model (SM) phase transitions:

Dark Matter

- WIMPs; axions; primordial black holes [DarkSide; HeRALD; SuperCDMS etc.]

Gravitational wave background

- could result from various phase transitions
- spectrum affected by phase-transition rate, the phase-boundary speed, and the defect dynamics [LISA; NANOGrav]

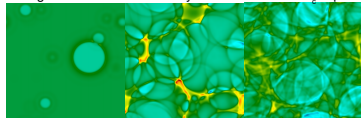
Cosmological defects

- cosmic strings; magnetic monopoles; domain walls; textures

1st order phase transition (dramatic, release of latent heat)

- bubbles of the new phase form in the middle of the old phase
- expansion and collisions follow; waves and defects emerge [M. Hindmarsh *et al.*, SciPost Phys. Lect. Notes **24** (2021)]

Numerical simulation of a phase transition by nucleation of bubbles, homogeneous nucleation theory. Bubbles with $R > R_c$ expand.

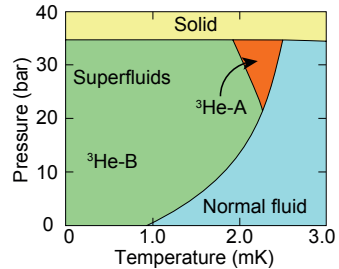


2nd order phase transition (continuous)

- defect formation via Kibble-Zurek mechanism; dynamics for GW

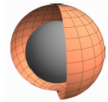
Helium-3: laboratory test bed for the early-Universe phase transitions

- Firmly established unconventional spin-triplet p-wave superfluid with $S = L = 1$ and $G = SO(3)_{\mathbf{L}} \times SO(3)_{\mathbf{S}} \times U(1)_{\phi}$.
 - Quantum analogue of Standard Model's $G = SU(3) \times SU(2) \times U(1)$.
 - Diverse range of excitations, collective modes, and defects.
- Extremely pure sample at the lowest temperatures; even ^4He impurities “frozen” on the sample walls.
 - Ideal for phase-transition studies (both 1st and 2nd order).
- Due to Cooper pairs' internal structure, multiple stable superfluid phases exist.



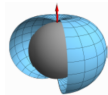
- First-order phase transition between $^3\text{He-A}$ and $^3\text{He-B}$.
- $^3\text{He-B}$, pseudo-isotropic: long-range order in relative orientation of $\hat{\mathbf{l}}$ and $\hat{\mathbf{s}}$:

$$A_{\mu j} = e^{i\phi} \Delta R_{\mu j}(\hat{\mathbf{n}}, \theta); \quad \Psi = e^{i\phi} \Delta \left(\begin{array}{c} L_z = 1, S_z = -1 \\ \text{diagram} \end{array} + \begin{array}{c} L_z = 0, S_z = 0 \\ \text{diagram} \end{array} + \begin{array}{c} L_z = -1, S_z = 1 \\ \text{diagram} \end{array} \right), L_z = -S_z$$



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

$$A_{\mu j} = e^{i\phi} \Delta \hat{d}_{\mu}(\hat{m}_j + i\hat{n}_j); \quad \Psi = e^{i\phi} \Delta \left(\begin{array}{c} L_z = 1, S_z = 1 \\ \text{diagram} \end{array} + \begin{array}{c} L_z = 1, S_z = -1 \\ \text{diagram} \end{array} \right)$$



[Gap illustrations by J. Sauls]

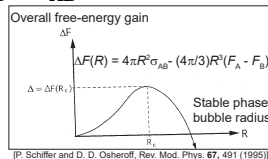
A-to-B phase nucleation puzzle

- The mechanism of the first-order phase transition between $^3\text{He-A}$ and $^3\text{He-B}$, 50+ years after its discovery, is still unresolved.
- Intrinsic processes predict lifetime of metastable supercooled A phase larger than the age of the Universe due to large critical size of the B-phase bubble, $R_c = 2\sigma_{AB}/\Delta F_{AB} \sim 1\mu\text{m}$.

[A. J. Leggett, JLTP **87**, 571 (1992)]

- Homogeneous nucleation by thermal fluctuations.
- Macroscopic quantum tunnelling.
 - Can be possibly accelerated by 'resonance' effects.

[S.-H. Henry Tye and D. Wohns, PRB **84**, 184518 (2011)]

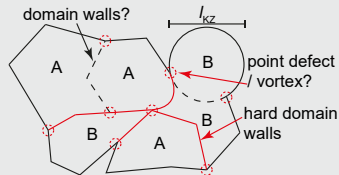


- However, in the lab the phase transitions are routinely observed, thus very likely triggered by extrinsic means. These need to be understood — and cancelled if possible — to gain access to any intrinsic mechanisms.
 - Impurities / rough surfaces / textural singularities → Cooling-rate dependence.
 - Seeds or surface pockets as a source → History dependence / catastrophe line.
 - **Nucleation by radiation ⇒ Stochastic process.**

Kibble-Zurek mechanism in cosmology and helium-3

Principle

- During a rapid continuous (2nd order) phase transition, causally disconnected regions cooling through T_c independently choose local order-parameter minima.
⇒ As such seeds expand/shrink/merge, various types of defects can be created.
 - Originally proposed for cosmological phase transitions by Kibble:
[T.W.B. Kibble, J. Phys. A **9**, 1387 (1976)]
 - Expanded to superfluid physics by Zurek:
[W.H. Zurek, Nature **317**, 505 (1985)]



Key measurables in helium-3

- Size of seeds at time t_{fr} : $l_{KZ} = a\xi_0(\tau_Q/\tau_0)^{1/4}$.
 - $\tau_0 = \xi_0/v_F \sim 1 \text{ ns}$ is the order-parameter relaxation time.
 - $\tau_Q^{-1} = \partial_t(T/T_c)$ is the cooldown rate at T_c .
 - $\tau_{\text{fr}} = \sqrt{\tau_Q \tau_0}$ is the freeze-out time, before which $\xi(T) = \xi_0/\sqrt{1 - T/T_c}$ longer than the causal horizon (system not in equilibrium).

Kibble-Zurek mechanism in cosmology and helium-3

Vortex formation in neutron-irradiated superfluid ^3He as an analogue of cosmological defect formation

V. M. H. Ruutu*, V. B. Eltsov†, A. J. Gill‡§, T. W. B. Kibble‡, M. Krusius*, Yu. G. Makhlin*, B. Plaçais†, G. E. Volovik*|| & Wen Xu*

* Low Temperature Laboratory, Helsinki University of Technology, 02150 Espoo, Finland
† Kapitza Institute for Physical Problems, 117334 Moscow, Russia
‡ Blackett Laboratory, Imperial College, London SW7 2BZ, UK
§ T-6 Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
|| Landau Institute for Theoretical Physics, 117334 Moscow, Russia
¶ Laboratoire de Physique de la Matière Condensée de l'École Normale Supérieure, CNRS URA 1437, F-75231 Paris Cedex 05, France

Laboratory simulation of cosmic string formation in the early Universe using superfluid ^3He

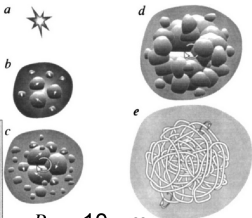
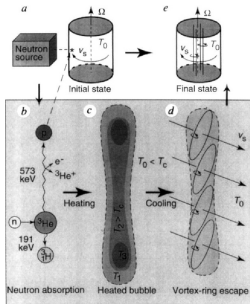
C. Bäuerle*, Yu. M. Bunkov*, S. N. Fisher*, H. Godfrin* & G. R. Pickett†

* Centre de Recherches sur les Très Basses Températures, Centre National de la Recherche Scientifique, BP 166, 38042 Grenoble Cedex 9, France
† School of Physics and Chemistry, Lancaster University, Lancaster LA1 4YB, UK

332

NATURE · VOL 382 · 25 JULY 1996

334



$$\begin{aligned} R_b &\sim 10 \mu\text{m} \\ \tau_Q &\sim 1 \mu\text{s} \\ l_{\text{KZ}} &\sim 1 \mu\text{m} \\ \tau_{\text{fr}} &\sim 10 \text{ ns} \end{aligned}$$

Key measurables in helium-3

- Size of seeds at time t_{fr} : $l_{\text{KZ}} = a\xi_0(\tau_Q/\tau_0)^{1/4}$.
- $\tau_0 = \xi_0/v_F \sim 1 \text{ ns}$ is the order-parameter relaxation time.
- $\tau_Q^{-1} = \partial_t(T/T_c)$ is the cooldown rate at T_c .
- $\tau_{\text{fr}} = \sqrt{\tau_Q \tau_0}$ is the freeze-out time, before which $\xi(T) = \xi_0/\sqrt{1 - T/T_c}$ longer than the causal horizon (system not in equilibrium).

Selected for a Viewpoint in Physics
PHYSICAL REVIEW LETTERS

week ending
16 DECEMBER 2016

Observation of Half-Quantum Vortices in Topological Superfluid ^3He

S. Autti,^{1,2} V. V. Dmitriev,³ J. T. Mäkinen,¹ A. A. Soldatov,^{2,3} G. E. Volovik,^{1,4} A. N. Yudin,² V. V. Zazhakov,¹ and V. B. Eltsov¹

¹Low Temperature Laboratory, Department of Applied Physics, Aalto University, P.O. Box 15100, FI-00076 AALTO, Finland

²P. L. Kapitza Institute for Physical Problems of RAS, 119334 Moscow, Russia

³Moscow Institute of Physics and Technology, 141700 Dolgoprudny, Russia

⁴Landau Institute for Theoretical Physics, 142432 Chernogolovka, Russia

(Received 24 August 2016; published 14 December 2016)

$$\begin{aligned} R_b &\sim 1 \text{ mm}, a \sim 1 \\ \tau_Q &\sim 10^2 - 10^6 \text{ s} \\ l_{\text{KZ}} &\sim 100 \mu\text{m} \\ \tau_{\text{fr}} &\sim 1 - 10 \text{ ms} \end{aligned}$$

PHYSICAL REVIEW LETTERS 127, 115702 (2021)

Editors' Suggestion

Featured in Physics

Suppressing the Kibble-Zurek Mechanism by a Symmetry-Violating Bias

J. Rystö,¹ J. T. Mäkinen,^{1,2} S. Autti,^{1,2} T. Kamppinen,¹ G. E. Volovik,^{1,3} and V. B. Eltsov¹

¹Department of Applied Physics, Aalto University, P.O. Box 15100, FI-00076 AALTO, Espoo, Finland

²Department of Physics, Lancaster University, Lancaster LA1 4YB, United Kingdom

³L.D. Landau Institute for Theoretical Physics, Moscow, 142432, Russia

(Received 14 June 2021; accepted 16 July 2021; published 8 September 2021)

Radiation-triggered phase transitions

■ Two competing mechanisms for radiation-triggered phase transitions.

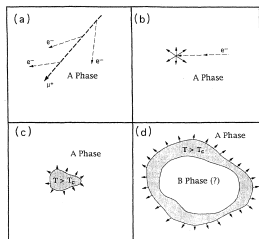
■ Baked Alaska [A. J. Leggett, Phys. Rev. Lett **53**, 1096 (1984) and JLTP **87**, 571 (1992); P. Schiffer *et al.*, Prog. Low Temp. Phys. **XIV**, 159 (1995)]

■ Cosmological “Kibble-Zurek” scenario [T. W. B. Kibble and G. E. Volovik, JETP Lett. **65**, 102 (1997);

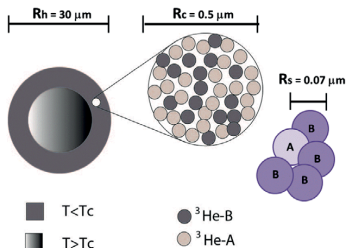
Yu. M. Bunkov and O. D. Timofeevskaya, Phys. Rev. Lett. **80**, 4927 (1998); Yu. M. Bunkov, J. Phys. Cond. Mat. **25**, 404205 (2013)]

■ Both rely on locally heating a bubble with $R_b > R_c$ above $T = T_c$ but differ in details on what happens as the bubble cools down. Ballistically expanding hot shell or diffusively rapidly shrinking hot blob? Single-phase nucleation or multitude of causally disconnected seeds?

[Yu. M. Bunkov and O. D. Timofeevskaya, PRL **82**, 3926 (1999)]



[P. Schiffer and D. D. Osheroff, Rev. Mod. Phys. **67**, 491 (1995)]



[Yu. M. Bunkov, J. Phys. Cond. Mat. **25**, 404205 (2013)]

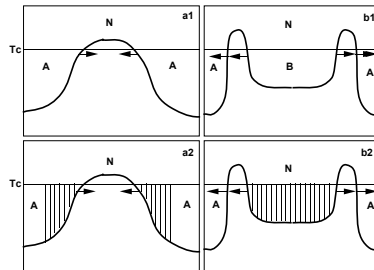


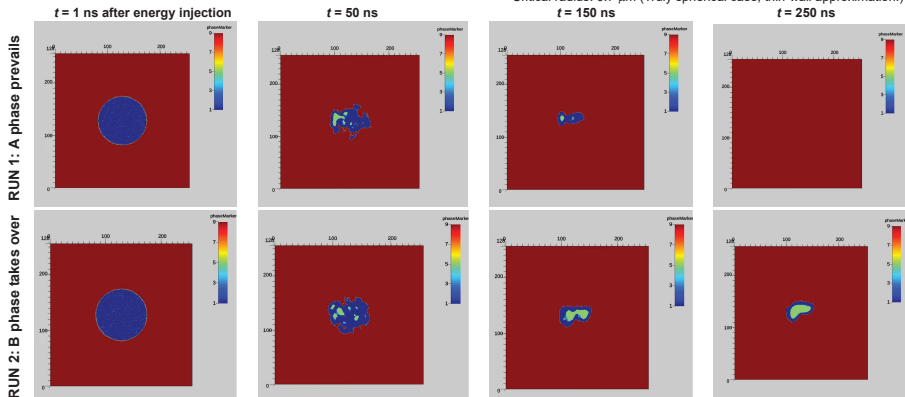
FIG. 1. The different scenario of transitions after a local heating. Vertical lines indicate a region of independently nucleated superfluid seeds.

Simulating the phase transition: A vs. B phase during bubble collapse

- HPC simulations implementing time-dependent G-L formalism to study far-from equilibrium process of local energy injection and the subsequent quench through T_c . [M. Hindmarsh *et al.*, J. Low Temp. Phys. **215**, 495 (2024)]
- Simulations show Kibble-Zurek mechanism being active, i.e., seeds of A/B phase are initially created followed by slow dynamics of them expanding/shrinking/combining. Applies regardless of the hot bubble cooling diffusively (assumed here) or via ballistically expanding hot shell (BA).

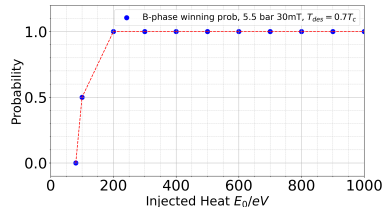
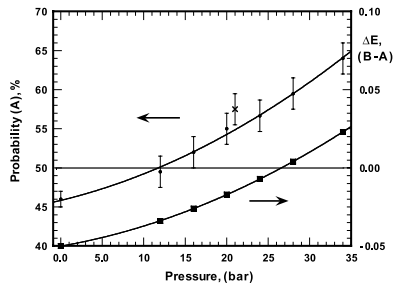
Colour coding: **A phase**; **B phase**; **AB-interface**

$P = 5.5$ bar; $T = 0.70 T_c$; $H = 30$ mT; Initial hot blob radius: $1.2\text{ }\mu\text{m}$
Critical radius: $0.7\text{ }\mu\text{m}$ (Truly spherical case, thin-wall approximation.)



Simulating the phase transition: Stochasticity

[Y. Bunkov, J. Phys.: Condens. Matter **25**, 404205 (2013)]



- A single-seed probability of ending into the A or the B phase has been calculated/simulated before (and confirmed by us) → Laptop.
- In realistic situation the number of K-Z seeds is $10^2 - 10^3$ within R_c radius bubble with complex evolution driven by inter-seed dynamics → HPC simulations.

See dyGiLa project (<https://dygila.github.io>).

- Previous experiments at 34 bar suggested that ~ 100 candidate events required in order to see one A-to-B phase transition. Reason not given.

[P. Schiffer and D. D. Osheroff, Rev. Mod. Phys. **67**, 491 (1995)]

- Present simulations suggest that even one event is enough as long as the heated bubble is bigger than a threshold size which can be more than R_c and likely depends on P and T (to be confirmed).

Simulating the phase transition: defects

- Earlier experimental studies of Kibble-Zurek mechanism in helium-3 concentrated on defect formation.

[V.M.H. Ruutu *et al.*, Nature **382**, 334 (1996); C. Bäuerle *et al.*, Nature **382**, 332 (1996); S. Autti *et al.*, Phys. Rev. Lett. **117**, 255301 (2016); J. Rysti *et al.*, Phys. Rev. Lett. **127**, 115702 (2021)]

- Recent simulations show the relevance of K-Z mechanism in creating both domain walls and vortices in thin films of $^3\text{He-A}$ undergoing a temperature quench through T_c .

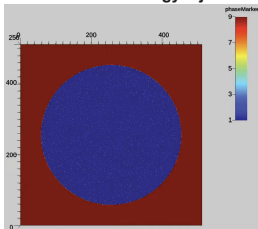
[N. Gluscevic and J.A. Sauls, Phys. Rev. B **111**, 214526 (2025)]

- Our simulations show formation of defects and vortices as well during the hot bubble quenches.

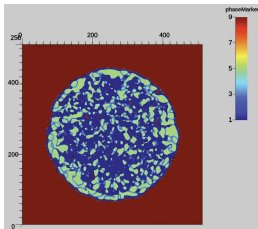
Colour coding: **A** phase; **B** phase; **AB**-interface; **BB** domain wall

$P = 5.5$ bar; $T = 0.70T_c$; $H = 30$ mT; Initial hot blob radius: $10.4\text{ }\mu\text{m}$
Critical radius: $0.7\text{ }\mu\text{m}$ (Truly spherical case, thin-wall approximation.)

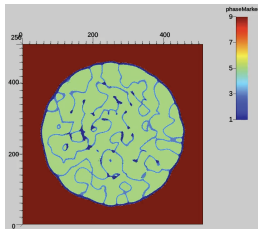
$t = 20$ ns after energy injection



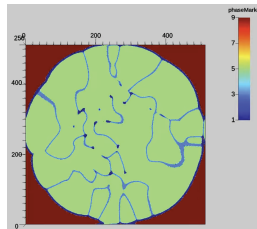
$t = 90$ ns



$t = 620$ ns



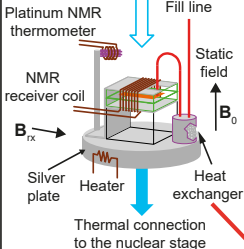
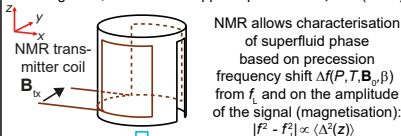
$t = 1960$ ns



SQUID-NMR and nanofabrication: Slab-shaped nanofluidic cavities

SQUID-amplified NMR:

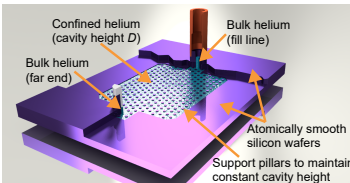
[L. V. Levitin *et al.*, App. Phys. Lett. **91**, 262507 (2007);
D. Drung *et al.*, IEEE Trans. Appl. Supercond. **17**, 699 (2007)]



Nanofluidic slab-shaped cavity:

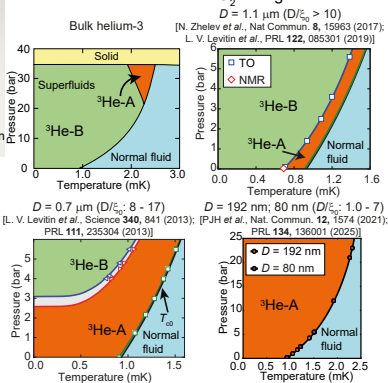
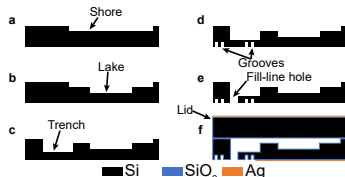
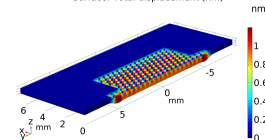
Standard nanofabrication techniques

- Photolithography, (deep) reactive ion etching, surface passivation, fusion bonding
[P. J. Heikkinen *et al.*, JLTP **215**, 477 (2024);
N. Zhelev *et al.*, Rev. Sci. Instr. **89**, 073902 (2018);
S. Dimov *et al.*, Rev. Sci. Instr. **81**, 013907 (2010)]



FEM modelling for cavity distortion:

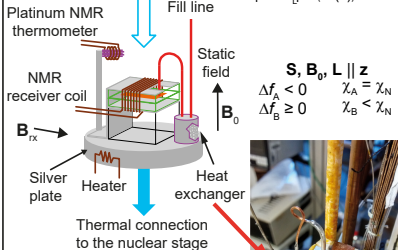
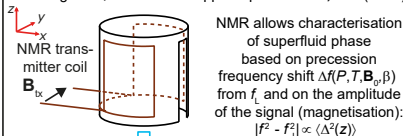
Ø100 µm pillars; 2.6 nm/bar
 Ø200 µm pillars; 1.0 nm/bar
 Surface: Total displacement (nm)



SQUID-NMR and nanofabrication: Multi-height cavities

SQUID-amplified NMR:

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



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



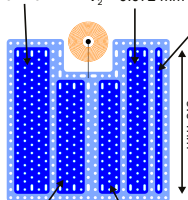
First measured hybrid cell with variable cavity height:

[P. J. Heikkinen *et al.*, JLT **215**, 477 (2024)]

- Five 'lakes' of different size fully isolated by shallow 'shore'.
- Lakes work as independent phase-transition volumes.
- Volume effect and statistics.
- Sliver of A phase ($T_c - T_{AB} \sim 10 \mu\text{K}$ at low P) is stable between normal state and the B phase at all pressures, stabilised by magnetic field ($B_0 \approx 30 \text{ mT}$) [Y. H. Tang *et al.*, PRL **67**, 1775 (1991)] and modest confinement ($D/\xi_0 > 100$).

Mask for nanofabrication

Lake 5 $V_5 = 0.120 \text{ mm}^3$ Lake 2 $V_2 = 0.072 \text{ mm}^3$ Lake 1 $V_1 = 0.024 \text{ mm}^3$

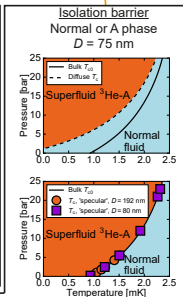
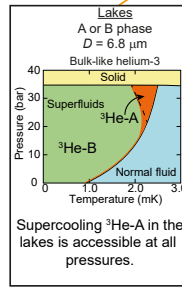
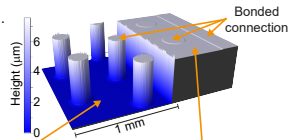


Volume ratios:
 $V_2 = 3.0V_1$
 $V_3 = 2.4V_1$
 $V_4 = 3.1V_1$
 $V_5 = 5.1V_1$

Lake 4 $V_4 = 0.075 \text{ mm}^3$ Lake 3 $V_3 = 0.056 \text{ mm}^3$



Optical profilometry

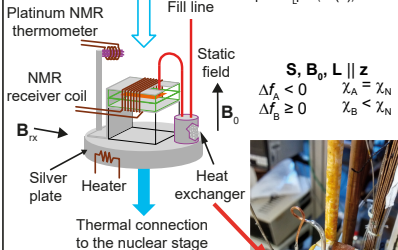
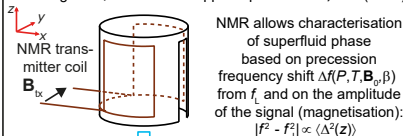


Superfluid ^4He boundary layer provides specular (mirror-like) surface scattering.
 - No suppression of T_c even at $D = 80 \text{ nm}$. [PJH *et al.*, PRL **134**, 136001 (2025)]

SQUID-NMR and nanofabrication: Multi-height cavities

SQUID-amplified NMR:

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



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

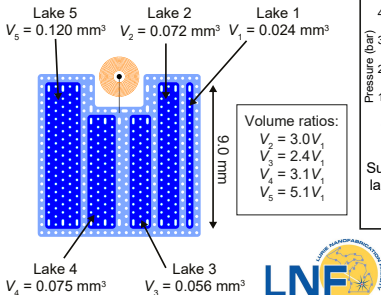


First measured hybrid cell with variable cavity height

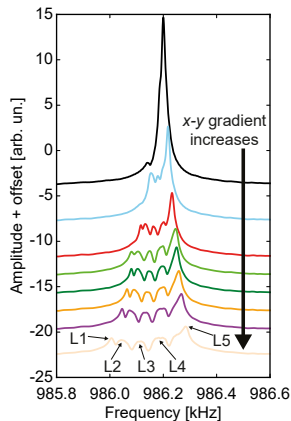
[P. J. Heikkinen *et al.*, JLT **215**, 477 (2024)]

- Five 'lakes' of different size fully isolated by shallow
- Lakes work as independent phase-transition volun
- Volume effect and statistics.
- Sliver of A phase ($T_c - T_{AB} \sim 10 \mu\text{K}$ at low P) is stat between normal state and the B phase at all press stabilised by magnetic field ($B_0 \approx 30 \text{ mT}$) [Y. H. Tang *et al.*, PRL **67**, 1775 (1991)] and modest confinement ($D/\xi_{s0} > 100$).

Mask for nanofabrication



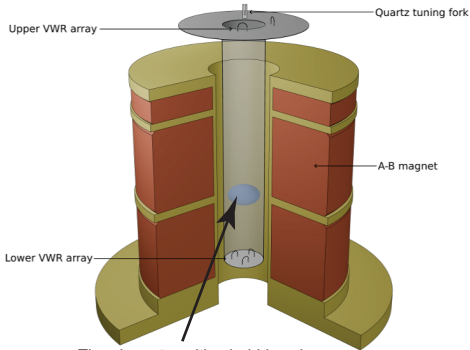
0 bar normal state NMR spectra



SQUID-NMR and nanofabrication: Multi-height cavities

Alternative approach:

[L. Whitehead *et al.*, JLTTP **221**, 249 (2025)]



The phase transition bubble volume, magnetically isolated from the walls.

1 hybrid cell with variable cavity height

[*et al.*, JLTTP **215**, 477 (2024)]

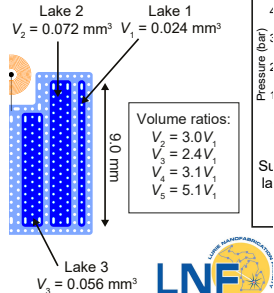
different size fully isolated by shallow independent phase-transition volume and statistics.

base ($T_c - T_{AB} \sim 10 \mu\text{K}$ at low P) is stable state and the B phase at all pressure magnetic field ($B_0 \approx 30 \text{ mT}$)

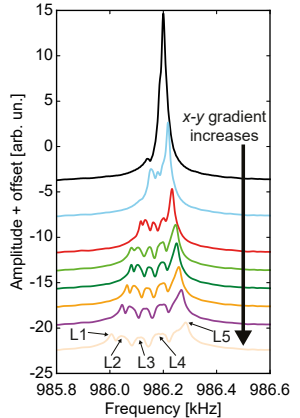
et al., PRL **67**, 1775 (1991)]

confinement ($D/\xi_{s0} > 100$).

2 fabrication



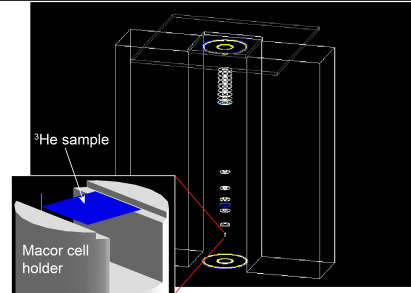
0 bar normal state NMR spectra



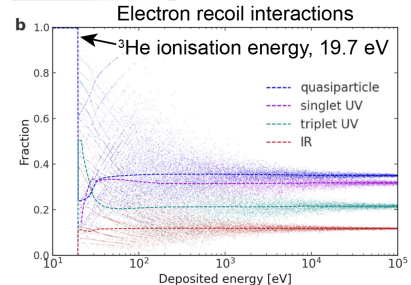
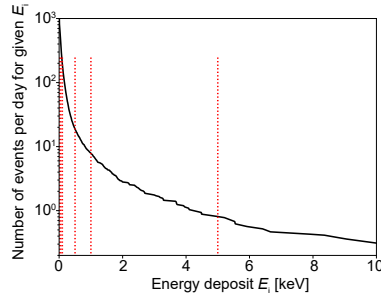
Radioactivity within the cryostat triggering the phase transitions

- Model ND2 cryostat and relevant materials inside and outside with Geant4 Monte Carlo particle interaction simulator:
 - Cosmic-ray events inside the sample are insignificant ($< 1/\text{day}$).
- Radioassay the Macor cell holder (contains radioactive ^{40}K isotope; β^- decay $^{40}\text{K} \rightarrow ^{40}\text{Ca}$):
 - Source of hundreds of 10–1000 eV events/day, primarily scattering; on average one third of the energy deposited as heat.

[S. Autti *et al.*, Eur. Phys. J. C **84**, 248 (2024)]



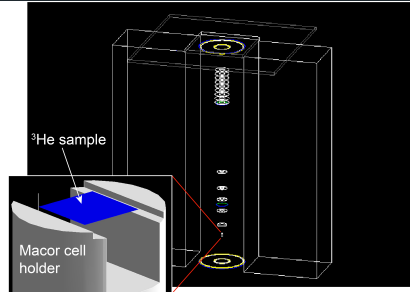
Energy, E_i [eV]	Events /day with $E > E_i$ [all lakes]
10	817
50	425
100	194
500	19
1000	8
5000	1



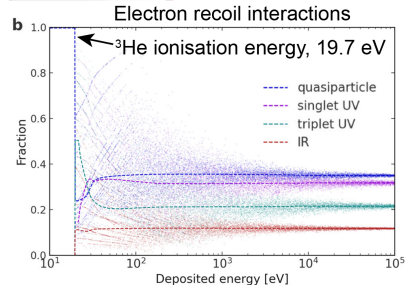
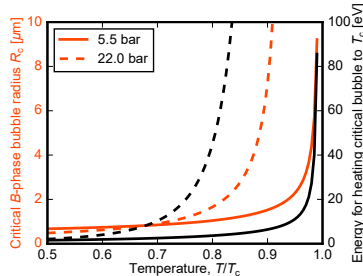
Radioactivity within the cryostat triggering the phase transitions

- Model ND2 cryostat and relevant materials inside and outside with Geant4 Monte Carlo particle interaction simulator:
 - Cosmic-ray events inside the sample are insignificant ($< 1/\text{day}$).
- Radioassay the Macor cell holder (contains radioactive ^{40}K isotope; β^- decay $^{40}\text{K} \rightarrow ^{40}\text{Ca}$):
 - Source of hundreds of 10–1000 eV events/day, primarily scattering; on average one third of the energy deposited as heat.

[S. Autti *et al.*, Eur. Phys. J. C **84**, 248 (2024)]



Energy, E_i [eV]	Events /day with $E > E_i$ [all lakes]
10	817
50	425
100	194
500	19
1000	8
5000	1



Ingredients for experiments

- **System to study:** Tiny nanofabricated phase-transition chambers surrounded only by atomically smooth surfaces and with no connection to outside world other than via $^3\text{He-A}$ or normal liquid.
- **Candidate phase-transition mechanism:** Kibble-Zurek during rapid quench of large enough bubbles which have been heated above T_c .
- **Candidate triggering heat source:** Macor cell holder inside the cryostat providing relevant heat flux into the sample via β^- decay.

Key figures of merit of experiments

- ND2 kept cold for 27 months in a row (from May 2023 until August 2025). 20 demagnetisation cycles.
- 2.5 TB raw data collected, 80% analysed.
- Around 1000 phase transitions detected, all of which suggested to be caused by radioactivity arising primarily from Macor.
 - Cryostat vibrations (tapping, pushing, LHe transfer etc.) do not trigger transitions.
 - Lifetime of metastable A phase varies between 1 hour and 400 hours, depending *only* on P and T .



Interpreting the NMR signatures

- Experimental procedure: cool the system down smoothly from normal state into $^3\text{He-A}$ and then past the first-order phase transition line into the $^3\text{He-B}$ regime until phase transition takes place.

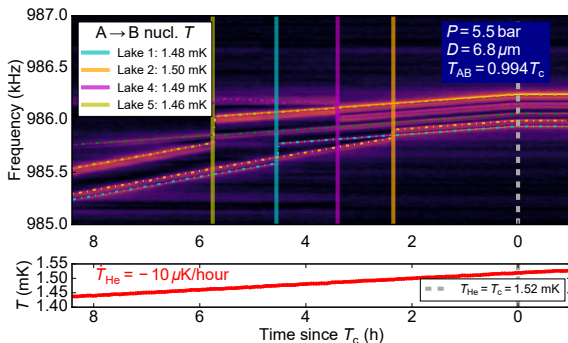
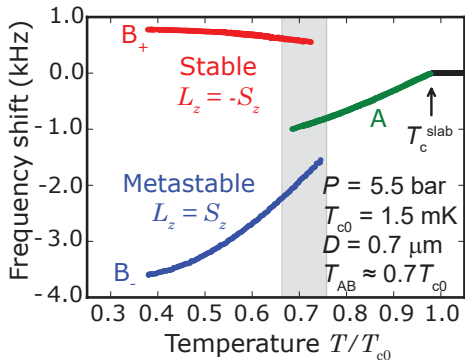
- Identification of superfluid phase: [L.V. Levitin *et al.*, Science **340**, 841 (2013); Phys. Rev. Lett. **111**, 235304 (2013)]

$^3\text{He-A}$ phase ($\hat{\mathbf{l}} = \hat{\mathbf{z}}; \hat{\mathbf{d}} \perp \hat{\mathbf{z}}$): $\Delta f = -\Delta f_A$, $\chi_A = \chi_N$. [P.J. Heikkinen *et al.*, Nat. Commun. **12**, 1574 (2021); Phys. Rev. Lett. **134**, 136001 (2025)]

$^3\text{He-B}_+$ phase ($\hat{\mathbf{n}} = \hat{\mathbf{z}}; \theta = 104^\circ$): $\Delta f \approx 0$, $\chi_{B_+} < \chi_N$.

$^3\text{He-B}_-$ phase ($\hat{\mathbf{n}} \perp \hat{\mathbf{z}}; \theta = \pi$): $\Delta f < -\Delta f_A$, $\chi_{B_-} < \chi_N$.

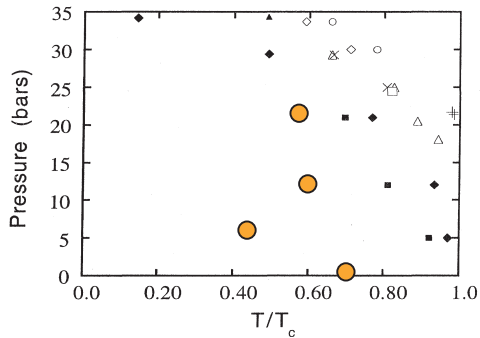
- Combination of field and confinement allows both the stable B_+ and metastable B_- configuration.



Strong supercooling and superheating observed. 22 bar example.

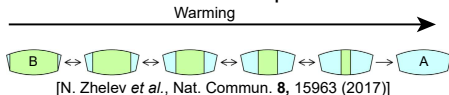
- Stronger supercooling than observed before (*orange circles*). Supercooled A phase accessible over full P range.
- No reason to believe more supercooling wouldn't be possible. **No catastrophe line. No sweep-rate dependence.**

Supercooling of $^3\text{He-A}$

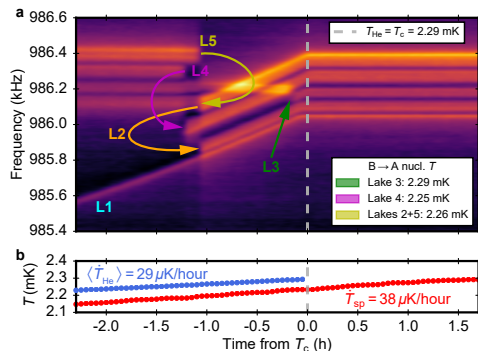


[P. Schiffer and D. D. Osheroff, Rev. Mod. Phys. **67**, 491 (1995)]

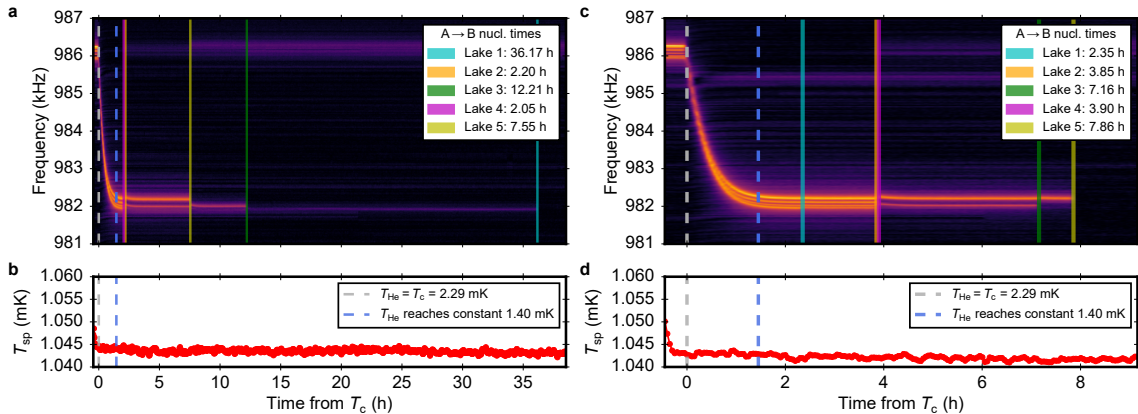
- Very vertical walls: no corners for A phase seeds to exist in when lakes in B phase. Shore is normal.



- Random process: different lakes superheat different degree upon various warm ups. $T_{AB} \approx 2.20$ mK.



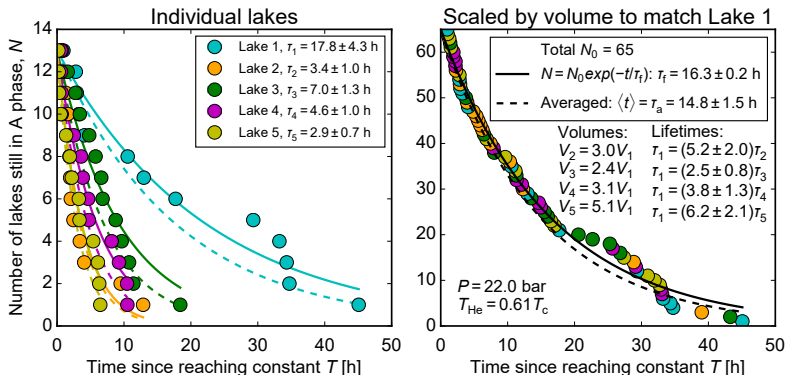
Waiting for nucleation events at constant T : stochastic process



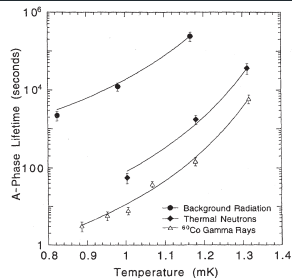
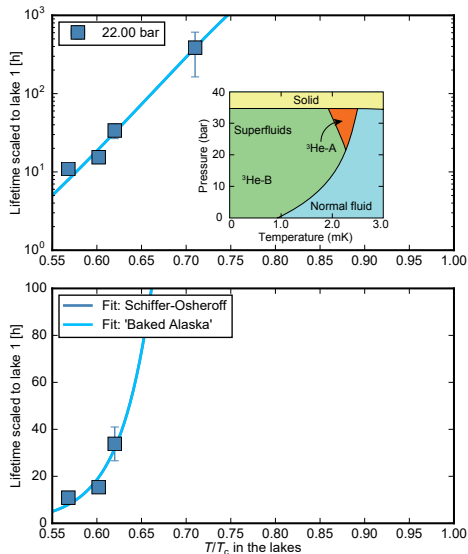
- Cool down fast to constant T and wait for all the lakes to transition ${}^3\text{He-A} \rightarrow {}^3\text{He-B}$.
- Transition times are random. Repeat multiple times to collect statistics.
- For such a stochastic process, the mean lifetime of metastable ${}^3\text{He-A}$ is an important parameter.

Collection of statistics: lifetime scales with volume

- An exponential distribution — characteristic of nucleation by a single stochastic process — for the lake lifetimes (analogous to e.g. radioactive decay) $\Rightarrow N = N_0 \exp(-t/\tau)$.
- Lifetime scales linearly with volume, as expected for radioactivity-triggered transitions. This makes measurements more efficient, allowing collapsing the data from different lakes to a single graph.



Monotonic T -dependence of the A-phase lifetime at high P



[P. Schiffer and D. D. Osheroff, Rev. Mod. Phys. **67**, 491 (1995)]

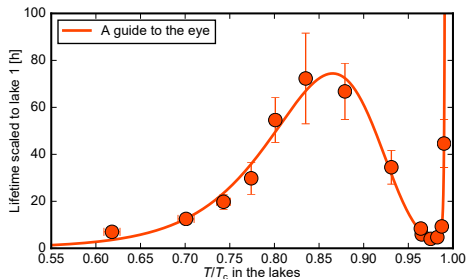
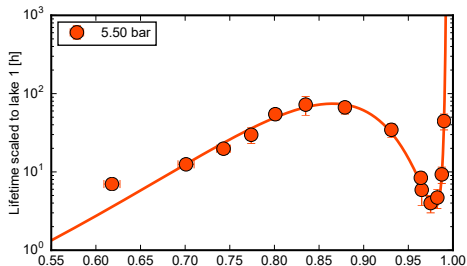
- Earlier experiments measured lifetime as a function of radiation intensity and magnetic field.

[P. Schiffer *et al.*, Prog. Low Temp. Phys. **XIV**, 159 (1995)]

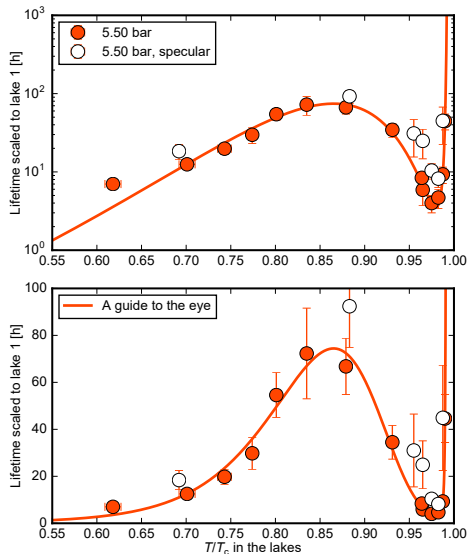
- Data fits inspired by Baked Alaska mechanism.
- BA predicts $\tau = C_0 \exp([R_c(T, P, B_0)/R_0]^N)$, where $N = 3$. Experiments found $N = 3/2$.
 - High P /low T assumed. Fitting parameters?
- Low- T data at 22.0 bar fits both forms very well.

Non-monotonic T -dependence of the A-phase lifetime at low P

- Non-monotonic dependence at low pressures not captured by earlier experiments or theories.

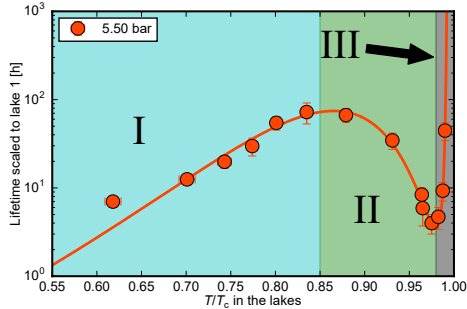


Non-monotonic T -dependence of the A-phase lifetime at low P

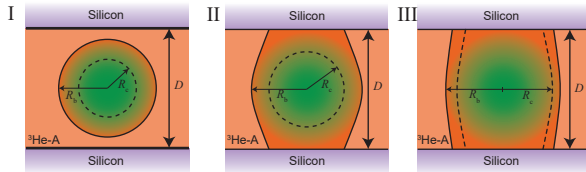


- Non-monotonic dependence at low pressures not captured by earlier experiments or theories.
- Specular boundary condition increases the mean-free path l and thus the cool down rate via $\tau_Q \propto R_b^2/(v_F l)$.

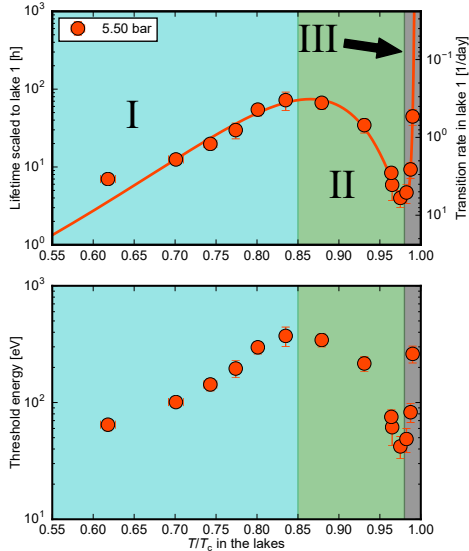
Non-monotonic T -dependence of the A-phase lifetime at low P



- Non-monotonic dependence at low pressures not captured by earlier experiments or theories.
- Specular boundary condition increases the mean-free path l and thus the cool down rate via $\tau_Q \propto R_b^2/(v_F l)$.
- **I**: 3-dimensional regime; $R_c < R_b < D/2$.
- **II**: 2-dimensional regime; $R_c < R_b \approx D/2$.
 - Size of region heated to $T > T_c$ hits the container height.
- **III**: Divergence regime; $R_c \rightarrow \infty$ as $T \rightarrow T_{AB}$.
- In our conditions $\tau_Q \sim 0.1 - 100 \mu\text{s}$, resulting in $\sim 10^2 - 10^3$ K-Z seeds within a sphere of radius R_c .

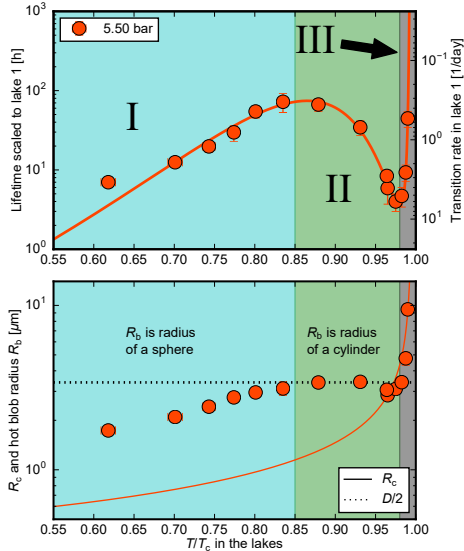


Non-monotonic T -dependence of the A-phase lifetime at low P



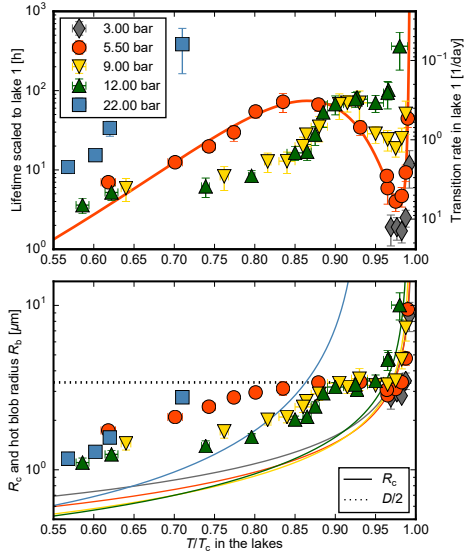
- Non-monotonic dependence at low pressures not captured by earlier experiments or theories.
- Specular boundary condition increases the mean-free path l and thus the cool down rate via $\tau_Q \propto R_b^2/(v_F l)$.
- **I:** 3-dimensional regime; $R_c < R_b < D/2$.
- **II:** 2-dimensional regime; $R_c < R_b \approx D/2$.
 - Size of region heated to $T > T_c$ hits the container height.
- **III:** Divergence regime; $R_c \rightarrow \infty$ as $T \rightarrow T_{AB}$.
- In our conditions $\tau_Q \sim 0.1 - 100 \mu\text{s}$, resulting in $\sim 10^2 - 10^3$ K-Z seeds within a sphere of radius R_c .
- Comparing τ^{-1} and energy flux from Geant4 gives a threshold energy, above which transition probability 1.

Non-monotonic T -dependence of the A-phase lifetime at low P



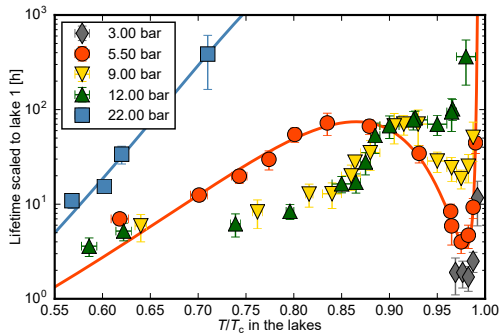
- Non-monotonic dependence at low pressures not captured by earlier experiments or theories.
- Specular boundary condition increases the mean-free path l and thus the cool down rate via $\tau_Q \propto R_b^2/(v_F l)$.
- **I**: 3-dimensional regime; $R_c < R_b < D/2$.
- **II**: 2-dimensional regime; $R_c < R_b \approx D/2$.
 - Size of region heated to $T > T_c$ hits the container height.
- **III**: Divergence regime; $R_c \rightarrow \infty$ as $T \rightarrow T_{AB}$.
- In our conditions $\tau_Q \sim 0.1 - 100 \mu\text{s}$, resulting in $\sim 10^2 - 10^3$ K-Z seeds within a sphere of radius R_c .
- Comparing τ^{-1} and energy flux from Geant4 gives a threshold energy, above which transition probability 1.
- In regime **II** the size of the 2D-shape heated region remains constant. Thus, as T increases and less energy is needed to create such a 'puck', τ decreases.
 - Perhaps this shape shields the K-Z process better.

Non-monotonic T -dependence of the A-phase lifetime at low P

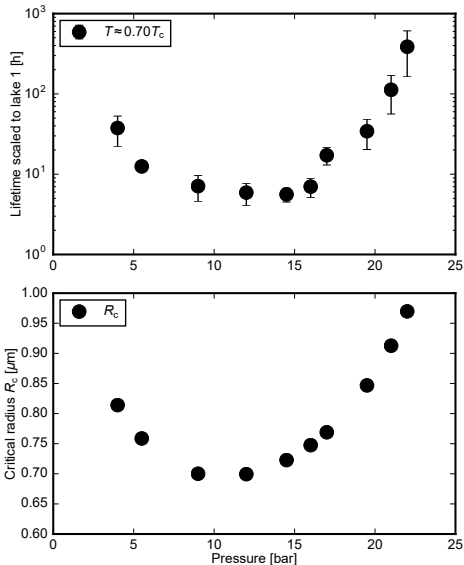


- Non-monotonic dependence at low pressures not captured by earlier experiments or theories.
- Specular boundary condition increases the mean-free path l and thus the cool down rate via $\tau_Q \propto R_b^2/(v_F l)$.
- I: 3-dimensional regime; $R_c < R_b < D/2$.
- II: 2-dimensional regime; $R_c < R_b \approx D/2$.
 - Size of region heated to $T > T_c$ hits the container height.
- III: Divergence regime; $R_c \rightarrow \infty$ as $T \rightarrow T_{AB}$.
- In our conditions $\tau_Q \sim 0.1 - 100 \mu\text{s}$, resulting in $\sim 10^2 - 10^3$ K-Z seeds within a sphere of radius R_c .
- Comparing τ^{-1} and energy flux from Geant4 gives a threshold energy, above which transition probability 1.
- In regime II the size of the 2D-shape heated region remains constant. Thus, as T increases and less energy is needed to create such a 'puck', τ decreases.
 - Perhaps this shape shields the K-Z process better.

Non-monotonic P -dependence of the A-phase lifetime



- Non-monotonic dependence on pressure characterised at $T \approx 0.7T_c$.
- Plausible explanation by the non-monotonic change of R_c .



Cosmological phase transitions in helium-3

- Universe was cooled down only once; helium-3 allows simulating this process over and over again.
- Its versatile multi-component order parameter gives access to both 1st and 2nd order phase transitions, and various different models.
- The present focus has been in characterising (experiments+simulations) the heated-bubble triggered phase transition from ${}^3\text{He-A}$ into ${}^3\text{He-B}$ by Kibble-Zurek mechanism.
 - Instead of a direct transition, part of ${}^3\text{He-A}$ heats into normal state and then converges into ${}^3\text{He-A}$ or ${}^3\text{He-B}$ as the bubble quenches through the 2nd order phase transition.

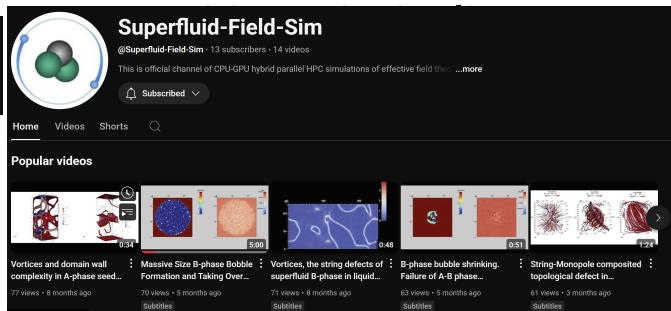
Future

- Characterise by simulations / analytically the microscopic details of evolution and clustering of the K-Z seeds forming the winning superfluid phase after the quench.
- Simulate over wide (T, P) the threshold size of the heated region for the B-phase win probability.
- Clarify the arguments proving K-Z vs single-seed and heat diffusion vs BA. Write a paper.
- Remove the radiation source(s) from the cryostat to access the possible intrinsic mechanism(s).
- Experimental probes for the predicted generation of defects and the phase-boundary dynamics?
- The cosmological analogue of a heated bubble in the early Universe? Metastable vs. stable versions of the early Universe (type of multiverse)?

Final thoughts



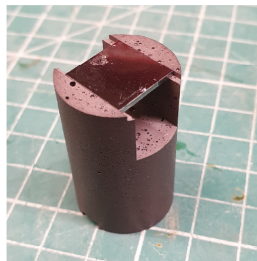
LIKE
&
SUBSCRIBE!



New cell holder:

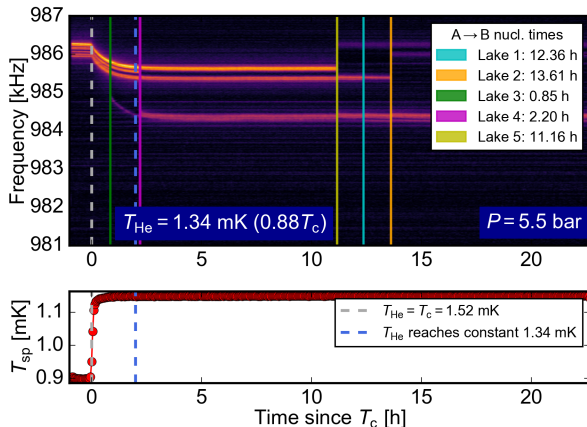
50-50 mixture of Stycast 1266 and fine Si powder (99.995%, trace metals).

Should we radioassay this material?

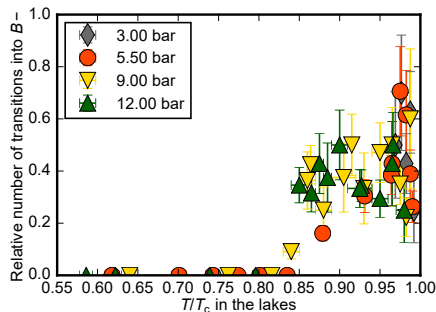


Transitions from A to either B_+ or B_- : Dimensionality?

- Combination of field and confinement allows both the stable (B_+ : $\hat{\mathbf{n}} = \hat{\mathbf{z}}$; $\theta = 104^\circ$; $\Delta f \approx 0$) and metastable (B_- : $\hat{\mathbf{n}} \perp \hat{\mathbf{z}}$; $\theta = \pi$; $\Delta f < 0$) configuration of the B-phase order parameter.
- Transitions taking place above $0.85T_c$ approximately 40% of time into B_- ; below $0.85T_c$ only transitions into B_+ . In few occasions a subsequent transition from B_- into B_+ .



- Related to heated region reaching the container height?



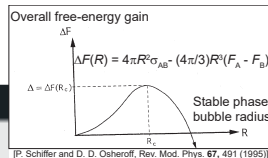
A-to-B phase nucleation puzzle

- The mechanism of the first-order phase transition between $^3\text{He-A}$ and $^3\text{He-B}$, 50+ years after its discovery, is still unresolved.
- Intrinsic processes predicted never to take place.

Intrinsic

- Homogeneous nucleation by thermal fluctuations alone.
 - Due to large critical size of B-phase bubble, $R_c = 2\sigma_{AB}/\Delta F_{AB} \sim 1\mu\text{m}$, predicts lifetime of metastable supercooled A phase larger than the age of the Universe. [A. J. Leggett, JLTTP **87**, 571 (1992)]
 - For comparison, nucleation of ice from supercooled water requires only $R_c \approx 4\text{nm}$.
- Macroscopic quantum tunnelling with or without resonant effects.
 - Theory suggests extremely slow nucleation rate for pure tunnelling. [D. Bailin and A. Love, J. Phys. A **13**, 271 (1980)]
 - Nucleation probability could have 'resonances' at certain combinations of temperature, pressure, and magnetic field. Possibly tunnelling via intermediate phases between $^3\text{He-A}$ and $^3\text{He-B}$.

[S.-H. Henry Tye and D. Wohns, PRB **84**, 184518 (2011)]



A-to-B phase nucleation puzzle

- However, in the lab the phase transitions are routinely observed, thus very likely triggered by extrinsic means.
 - Need to be understood – and cancelled if possible – to gain access to intrinsic mechanisms.

Extrinsic

- Nucleation by radiation. **Stochastic process.**
 - Experimentally shown that γ -rays and neutrons have a clear effect. Role of cosmic rays as background effect less clear. [P. Schiffer and D. D. Osheroff, Rev. Mod. Phys. **67**, 491 (1995)]
 - Various competing theoretical scenarios. [A. J. Leggett, PRL **53**, 1096 (1984); Yu. M. Bunkov and O. D. Timofeevskaya, PRL **80**, 4927 (1998)]
- Impurities / rough surfaces / textural singularities. **Likely to have a cooling-rate dependence.**
 - Flow of superfluid around sharp edges/corners due to thermal gradients or vibrations can nucleate B phase. [M. O'Keefe, B. Barker, D. D. Osheroff, Czech. J. Phys. **46**, 163 (1996)]
 - In a cell with non-polished surfaces nucleation predominantly occurs at certain locations.
[G. W. Swift and D. S. Buchanan, Jpn. J. Appl. Phys. **26**, 1828 (1987)]
- Seeds or surface pockets as a source. **History dependence.** [S. Balibar *et al.*, JLTP **120**, 293 (2000)]
 - Extremely rough surfaces (such as sintered heat exchangers) can house isolated volumes of distorted order parameter, connected to rest of the sample by narrow channels. [Y. Tian *et al.*, Nat. Commun. **14**, 148 (2023)]
 - **Catastrophe line.** [Kleinberg, Paulson, Webb, Wheatley, JLTP **17**, 521 (1974) and **23**, 725 (1976); P. J. Hakonen *et al.*, PRL **54**, 245 (1985)]

A-to-B phase nucleation puzzle

- However, in the lab the phase transitions are routinely observed, thus very likely triggered by extrinsic means.
 - Need to be understood – and cancelled if possible – to gain access to intrinsic mechanisms.

Extrinsic

- Nucleation by radiation. **Stochastic process.**
 - Experimentally shown that γ -rays and neutrons have a clear effect. Role of cosmic rays as background effect less clear. [P. Schiffer and D. D. Osheroff, Rev. Mod. Phys. **67**, 491 (1995)]
 - Various competing theoretical scenarios. [A. J. Leggett, PRL **53**, 1096 (1984); Yu. M. Bunkov and O. D. Timofeevskaya, PRL **80**, 4927 (1998)]
- ~~■ Impurities / rough surfaces / textural singularities. **Likely to have a cooling-rate dependence.**~~
 - ~~■ Flow of superfluid around sharp edges/corners due to thermal gradients or vibrations can nucleate B phase. [M. O'Keefe, B. Barker, D. D. Osheroff, Czech. J. Phys. **46**, 163 (1996)]~~
 - ~~■ In a cell with non-polished surfaces nucleation predominantly occurs at certain locations.~~
~~[G. W. Swift and D. S. Buchanan, Jpn. J. Appl. Phys. **26**, 1828 (1987)]~~
- ~~■ Seeds or surface pockets as a source. **History dependence**~~ [S. Balibar *et al.*, JLTP **120**, 293 (2000)]
 - ~~■ Extremely rough surfaces (such as sintered heat exchangers) can house isolated volumes of distorted order parameter, connected to rest of the sample by narrow channels. [Y. Tian *et al.*, Nat. Commun. **14**, 148 (2023)]~~
 - ~~■ **Catastrophe line.** [Kleinberg, Paulson, Webb, Wheatley, JLTP **17**, 521 (1974) and **23**, 725 (1976); P. J. Hakonen *et al.*, PRL **54**, 245 (1985)]~~