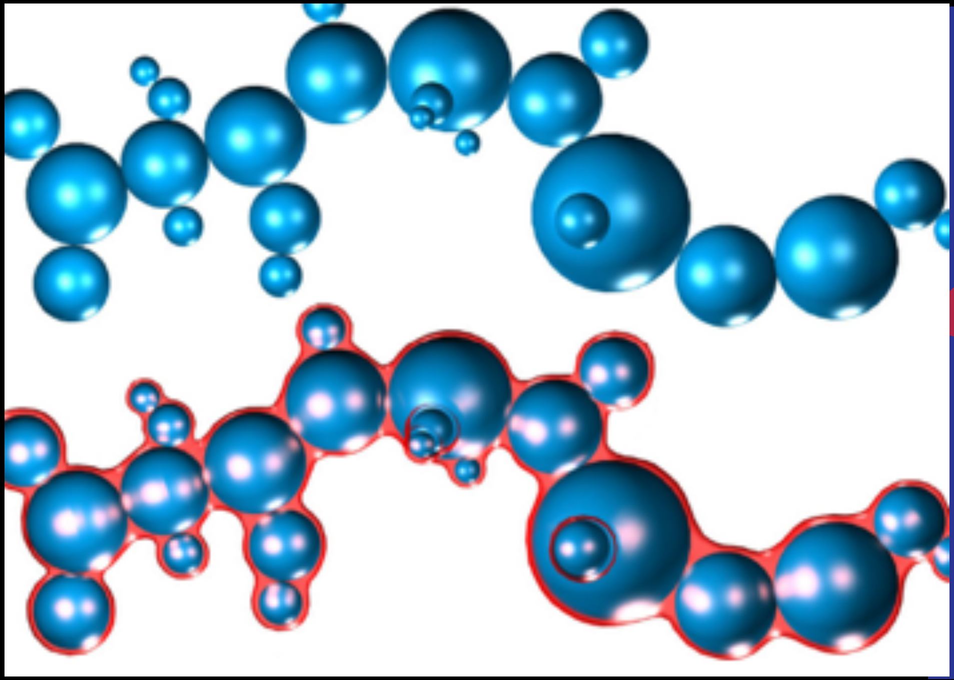
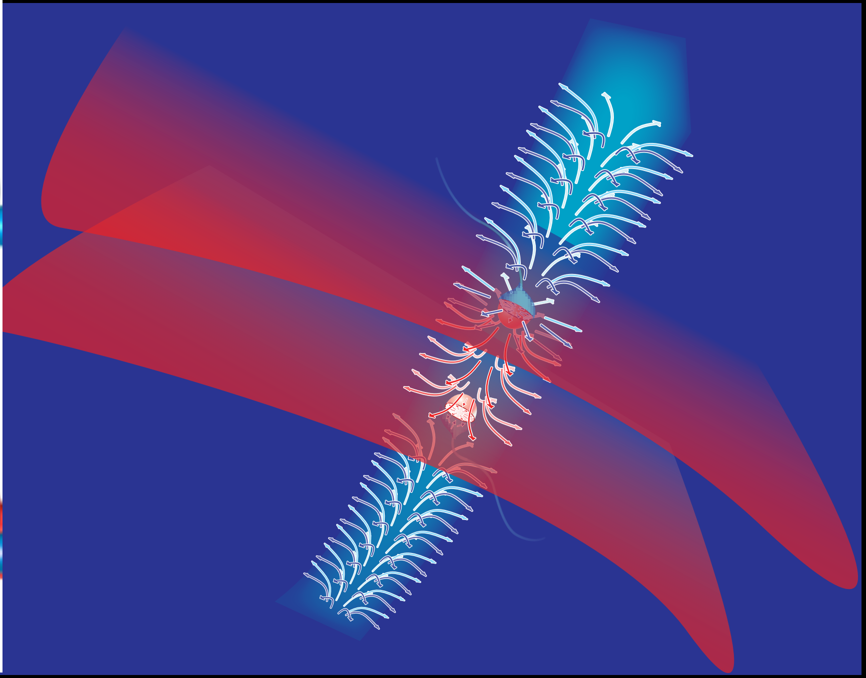
Ultra
Low
Temperature

Lancaster
University

# Superfluid $^3$He confined & in the AB interface

Rich Haley





Grand Challenges
in Quantum
Fluids and Solids

PENNSTATE

NSF

University at Buffalo
The State University of New York

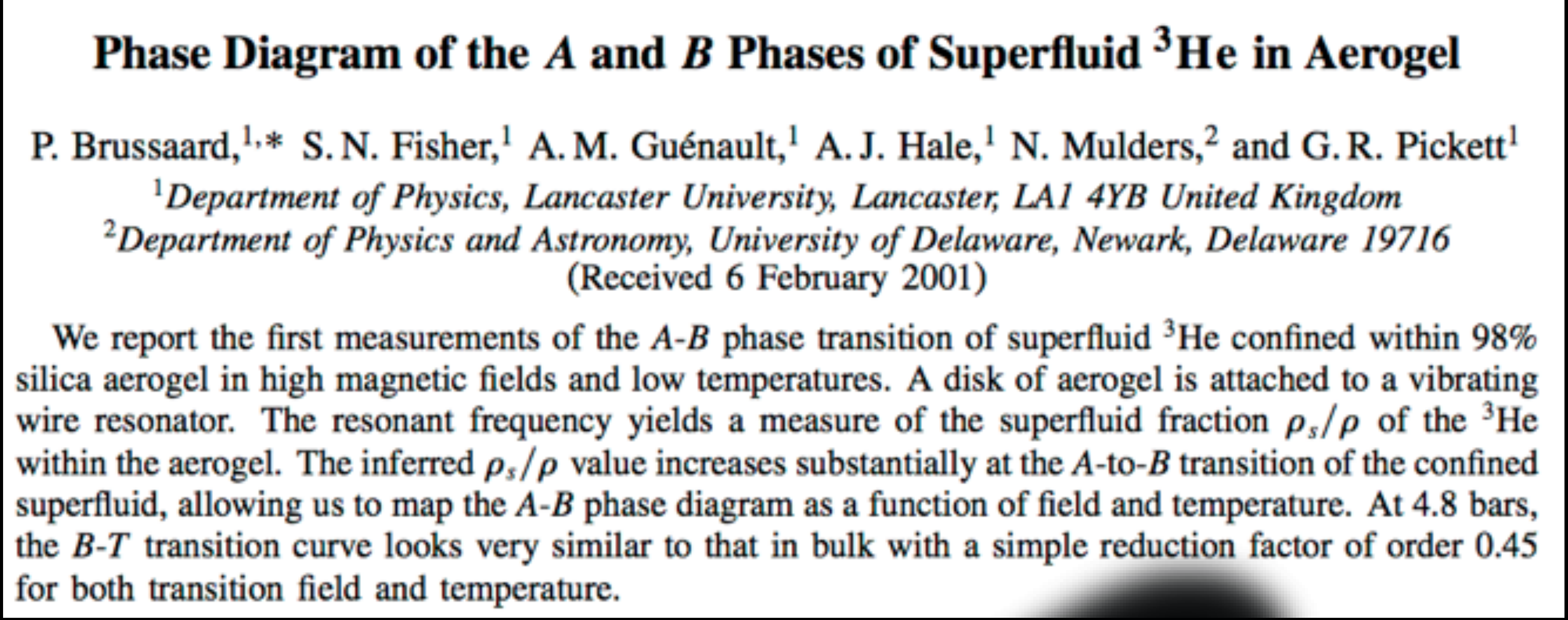
# Outline

Aerogel - disorder & confinement

- AB phase diagram
- Gapless superfluidity
- Anisotropy
- Substrate for solid helium-3
- What's next…

Field-stabilised AB interface; gap suppression & engineering

- Phase diagram
- Thermodynamic properties
- Open questions…



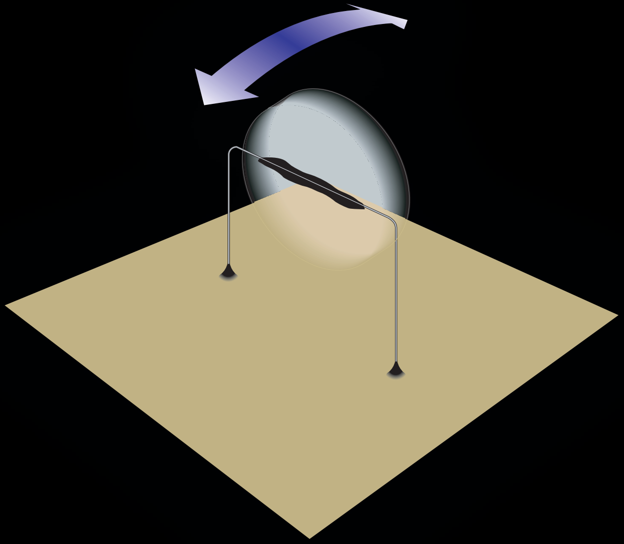
# Phase Diagram of the *A* and *B* Phases of Superfluid $^3$He in Aerogel

P. Brussaard,[1,*] S. N. Fisher,[1] A. M. Guénault,[1] A. J. Hale,[1] N. Mulders,[2] and G. R. Pickett[1]
[1]*Department of Physics, Lancaster University, Lancaster, LA1 4YB United Kingdom*
[2]*Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716*

(Received 6 February 2001)

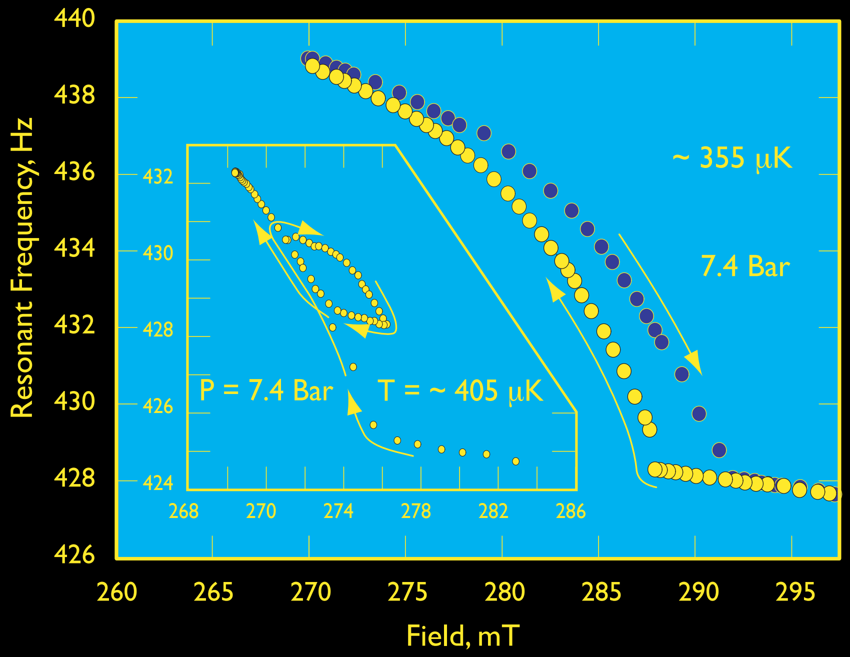
We report the first measurements of the *A*-*B* phase transition of superfluid $^3$He confined within 98% silica aerogel in high magnetic fields and low temperatures. A disk of aerogel is attached to a vibrating wire resonator. The resonant frequency yields a measure of the superfluid fraction $\rho_s/\rho$ of the $^3$He within the aerogel. The inferred $\rho_s/\rho$ value increases substantially at the *A*-to-*B* transition of the confined superfluid, allowing us to map the *A*-*B* phase diagram as a function of field and temperature. At 4.8 bars, the *B*-*T* transition curve looks very similar to that in bulk with a simple reduction factor of order 0.45 for both transition field and temperature.

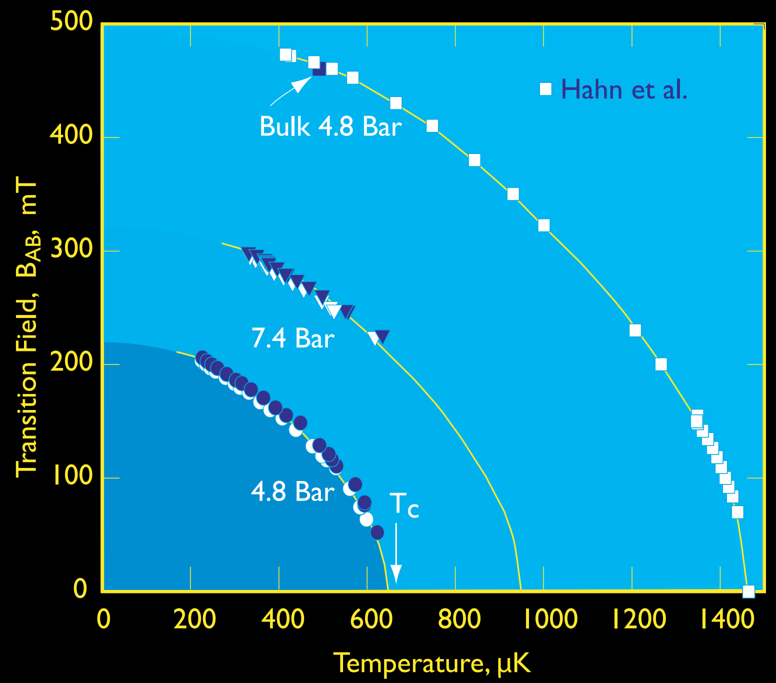
$$\frac{\rho_s}{\rho} = 1 - \frac{(f_0/f)^2 - 1}{(f_0/f_n)^2 - 1}$$



- ballistic quasiparticles, superfluid phase boundaries and confined geometries

# Phase Diagram of the *A* and *B* Phases of Superfluid $^3$He in Aerogel



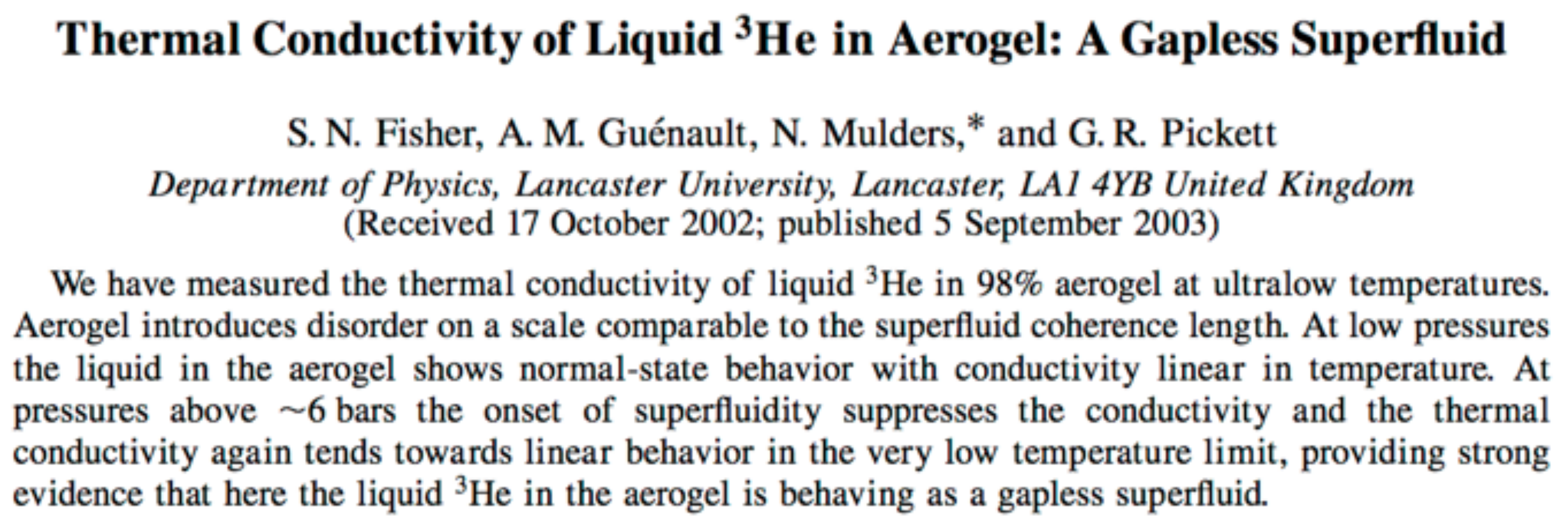


“Andronikashvili”
Superfluid density
AND flow dynamics

Pinning of AB interface (surface tension)

Supercooling/undermagnetization of A to B

Bulk transitions suppressed by 0.45 in both field and temperature

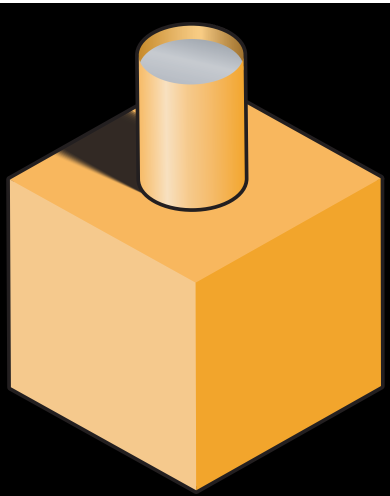


# Thermal Conductivity of Liquid $^3$He in Aerogel: A Gapless Superfluid

S. N. Fisher, A. M. Guénault, N. Mulders,* and G. R. Pickett
*Department of Physics, Lancaster University, Lancaster, LA1 4YB United Kingdom*

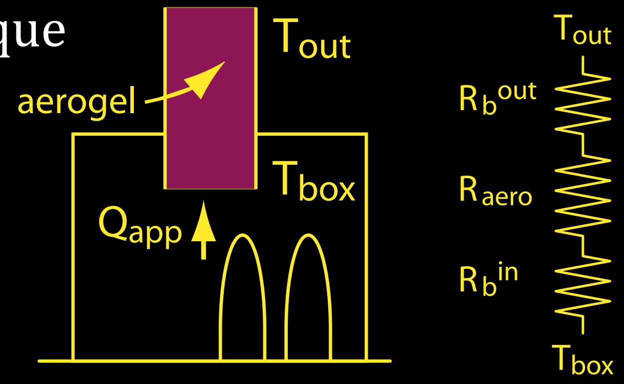
(Received 17 October 2002; published 5 September 2003)

We have measured the thermal conductivity of liquid $^3$He in 98% aerogel at ultralow temperatures. Aerogel introduces disorder on a scale comparable to the superfluid coherence length. At low pressures the liquid in the aerogel shows normal-state behavior with conductivity linear in temperature. At pressures above ~6 bars the onset of superfluidity suppresses the conductivity and the thermal conductivity again tends towards linear behavior in the very low temperature limit, providing strong evidence that here the liquid $^3$He in the aerogel is behaving as a gapless superfluid.



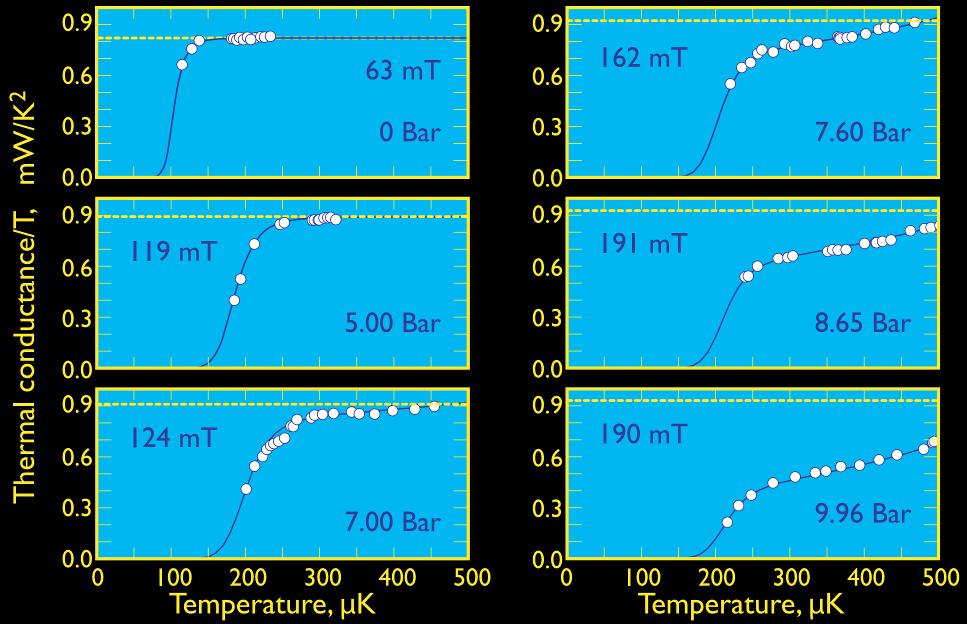
Black Body Radiator technique

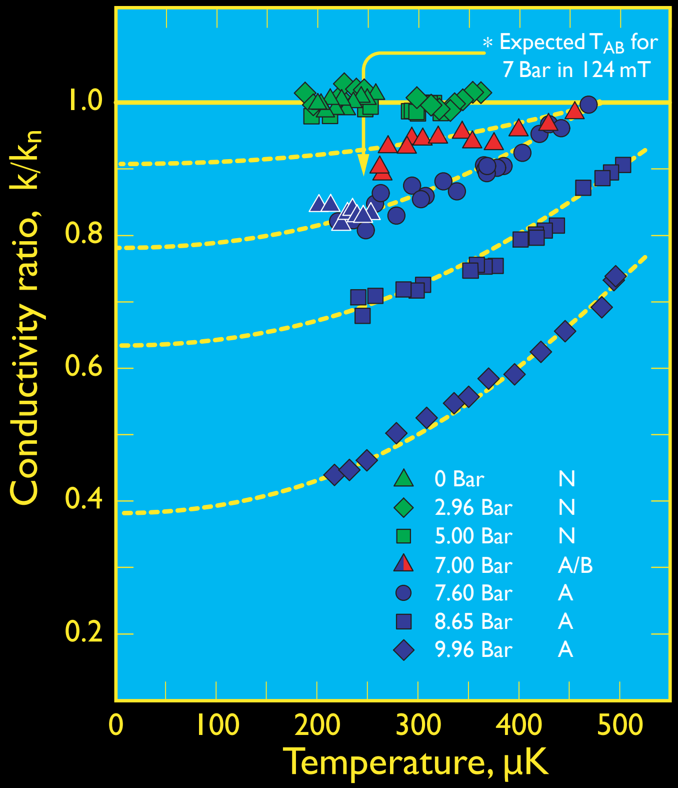
$$\kappa = \frac{L\dot{Q}}{A\Delta T}$$



- model substance with connections to such topics as superconductivity
- quasiparticle scattering from a bulk superfluid - aerogel superfluid interface

# Thermal Conductivity of Liquid $^3$He in Aerogel: A Gapless Superfluid

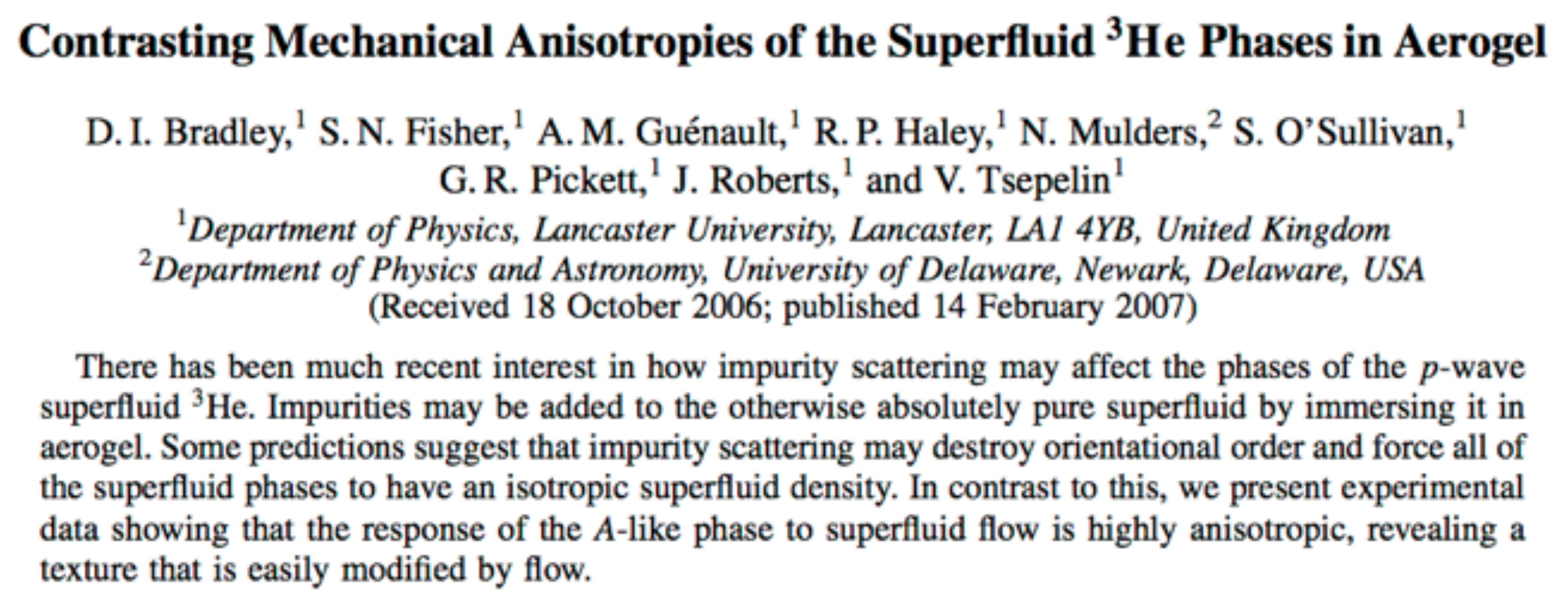




Boundary resistance “problem”

“Gapless” - finite DOS close to E=0 around Fermi surface

Transport across: S-N-S; S-Dirty SF-S.
S can be A phase (nodes) or B phase (isotropic)
Dirty SF can be A-like or B-like



# Contrasting Mechanical Anisotropies of the Superfluid $^3$He Phases in Aerogel

D. I. Bradley,[1] S. N. Fisher,[1] A. M. Guénault,[1] R. P. Haley,[1] N. Mulders,[2] S. O'Sullivan,[1]
G. R. Pickett,[1] J. Roberts,[1] and V. Tsepelin[1]
[1]*Department of Physics, Lancaster University, Lancaster, LA1 4YB, United Kingdom*
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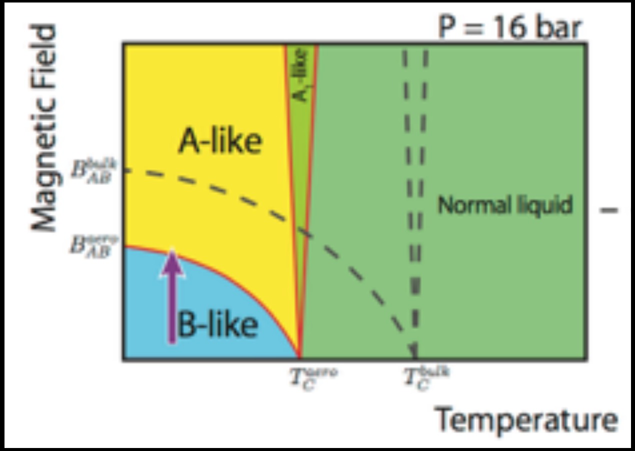
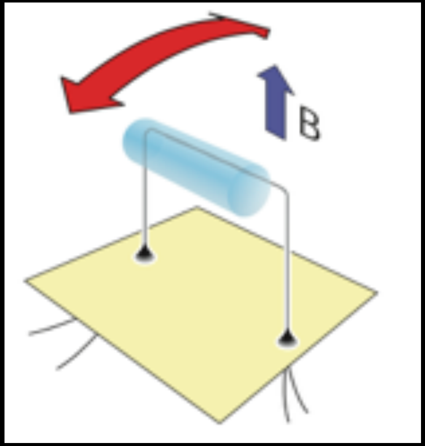
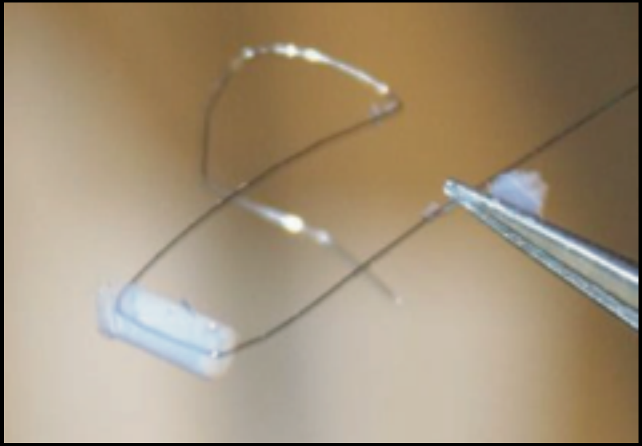
(Received 18 October 2006; published 14 February 2007)

There has been much recent interest in how impurity scattering may affect the phases of the *p*-wave superfluid $^3$He. Impurities may be added to the otherwise absolutely pure superfluid by immersing it in aerogel. Some predictions suggest that impurity scattering may destroy orientational order and force all of the superfluid phases to have an isotropic superfluid density. In contrast to this, we present experimental data showing that the response of the *A*-like phase to superfluid flow is highly anisotropic, revealing a texture that is easily modified by flow.

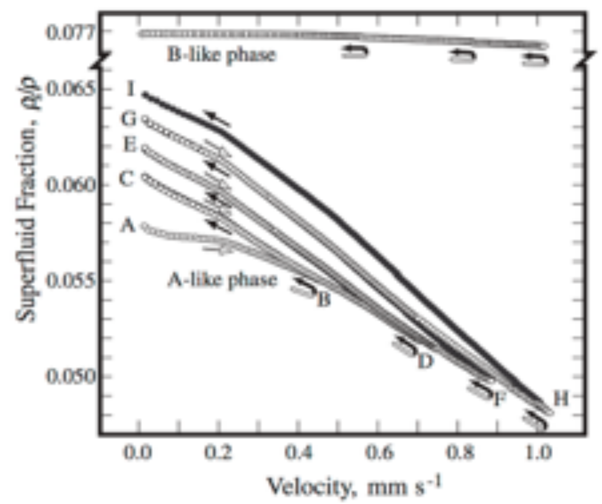


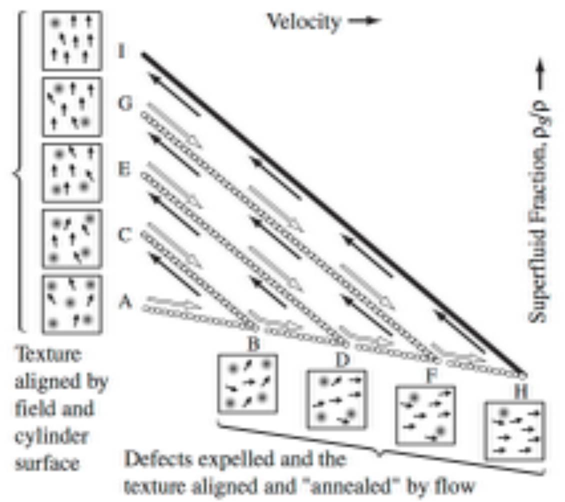


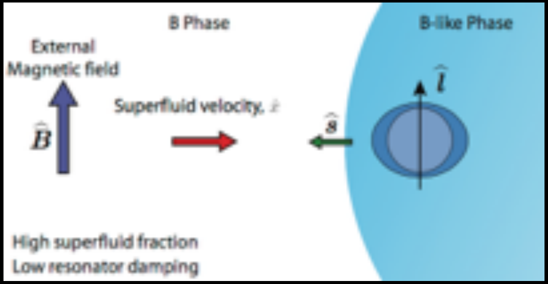


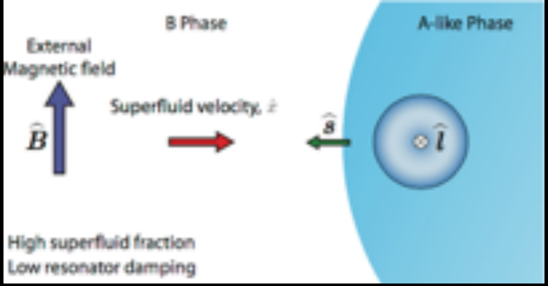
- impurities influence the various superfluid phases and the transitions between

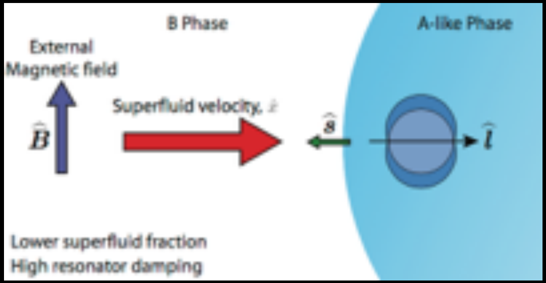
# Contrasting Mechanical Anisotropies of the Superfluid $^3$He Phases in Aerogel









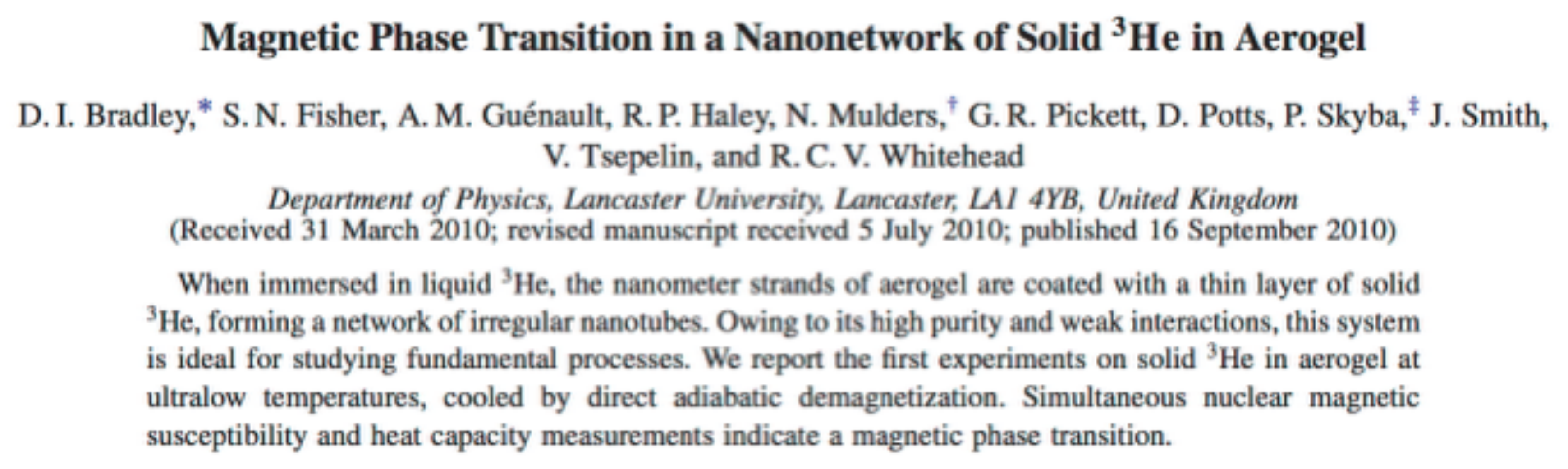


Anisotropic texture, modified by flow

Texture contains defects that can be healed

Texture has "active" response - can be combed

Proximity Effects?
Tuneable?
Control and engineering of gap structure at the bulk-aerogel interface.



## Magnetic Phase Transition in a Nanonetwork of Solid $^3$He in Aerogel

D. I. Bradley,* S. N. Fisher, A. M. Guénault, R. P. Haley, N. Mulders,† G. R. Pickett, D. Potts, P. Skyba,‡ J. Smith, V. Tsepelin, and R. C. V. Whitehead

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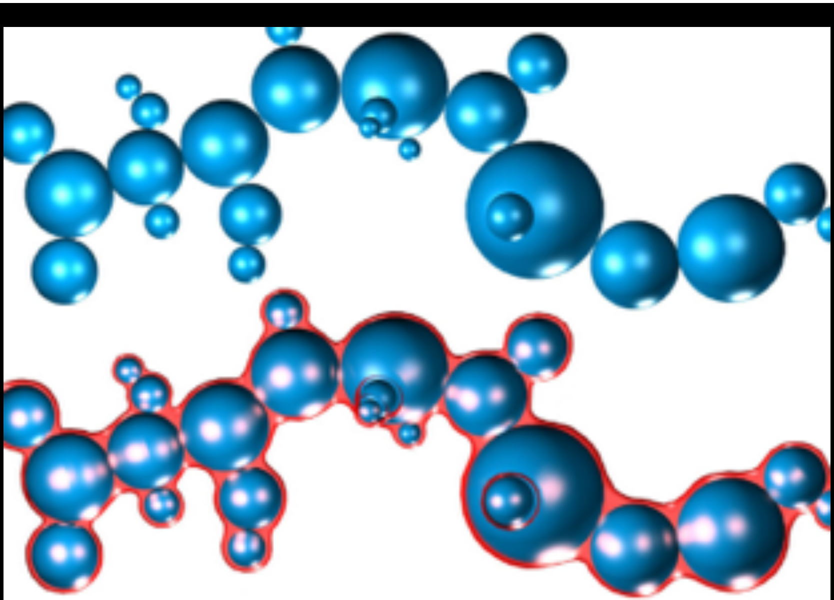
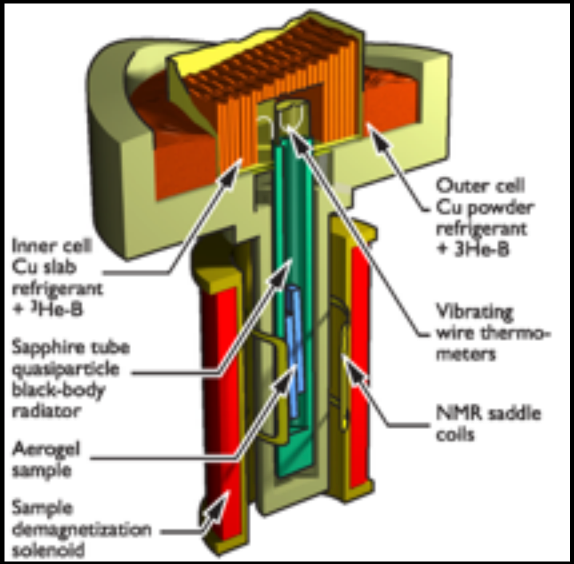
(Received 31 March 2010; revised manuscript received 5 July 2010; published 16 September 2010)

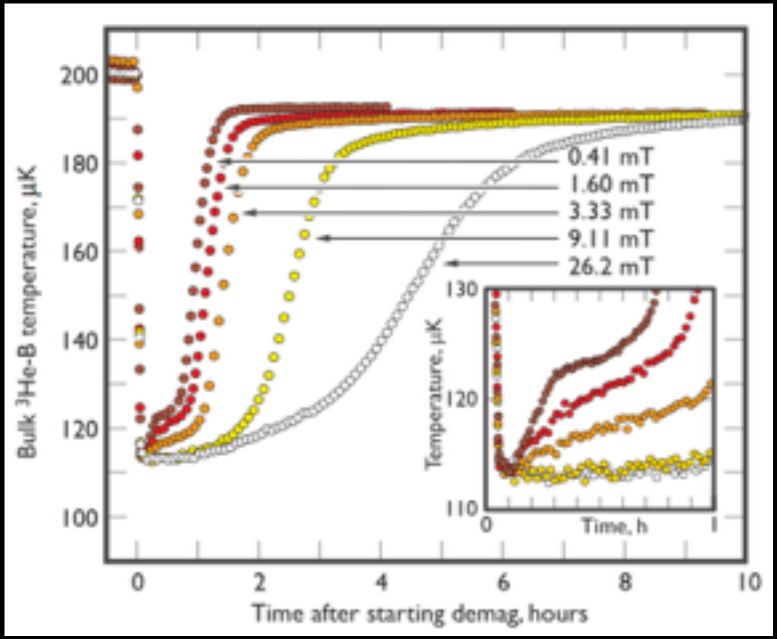
When immersed in liquid $^3$He, the nanometer strands of aerogel are coated with a thin layer of solid $^3$He, forming a network of irregular nanotubes. Owing to its high purity and weak interactions, this system is ideal for studying fundamental processes. We report the first experiments on solid $^3$He in aerogel at ultralow temperatures, cooled by direct adiabatic demagnetization. Simultaneous nuclear magnetic susceptibility and heat capacity measurements indicate a magnetic phase transition.

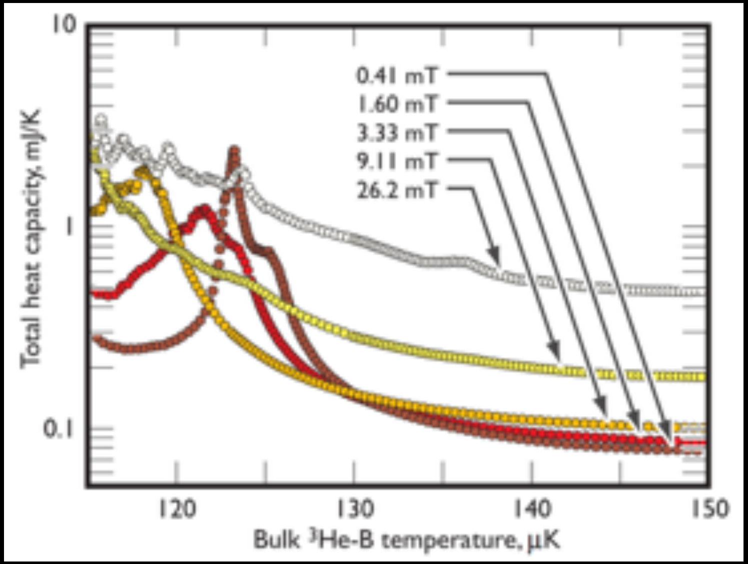


- few atomic layers of $^3$He atoms are adsorbed onto the silica strands
- near perfect thermal contact to the superfluid

# Magnetic Phase Transition in a Nanonetwork of Solid $^3$He in Aerogel





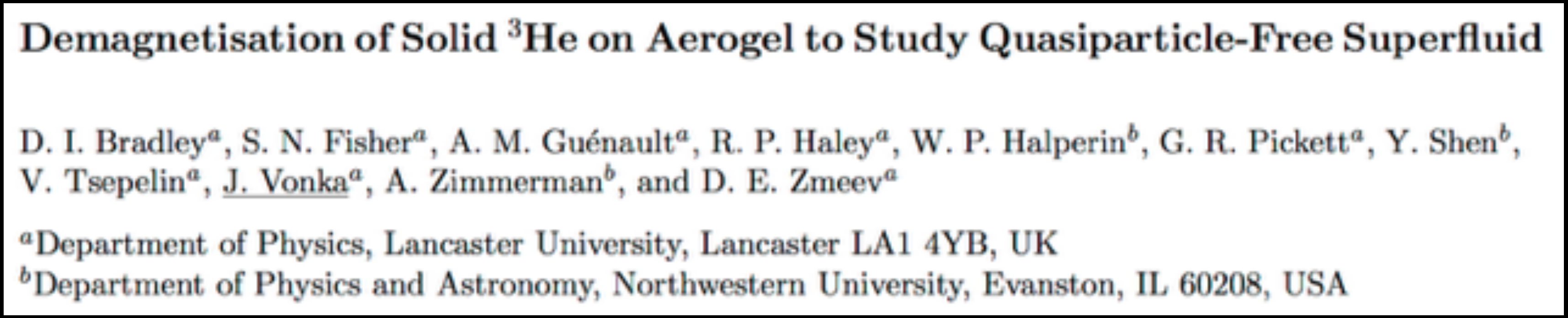


Cooling by demag of solid on strands

Evidence for magnetic phase transition

“Nanotubes” of solid $^3$He few atoms thick

Other substrates?



# Demagnetisation of Solid $^3$He on Aerogel to Study Quasiparticle-Free Superfluid

D. I. Bradley[a], S. N. Fisher[a], A. M. Guénault[a], R. P. Haley[a], W. P. Halperin[b], G. R. Pickett[a], Y. Shen[b], V. Tsepelin[a], J. Vonka[a], A. Zimmerman[b], and D. E. Zmeev[a]

[a]Department of Physics, Lancaster University, Lancaster LA1 4YB, UK
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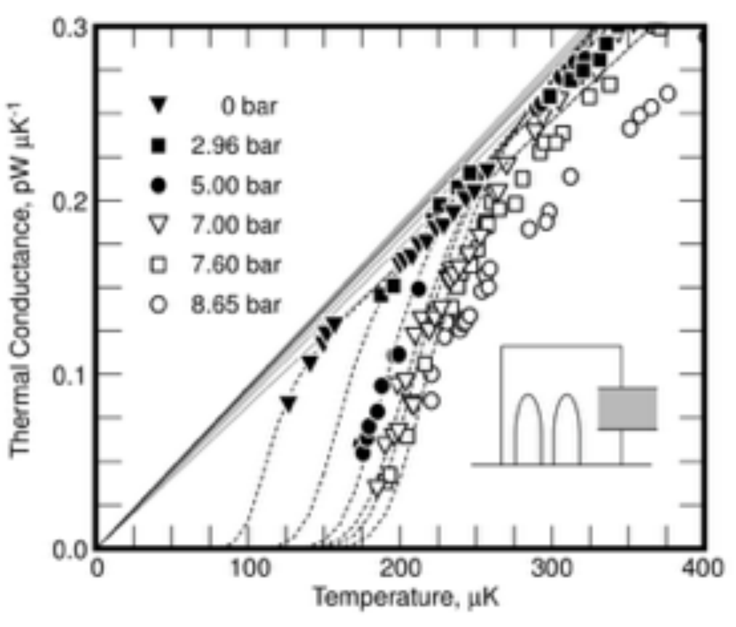
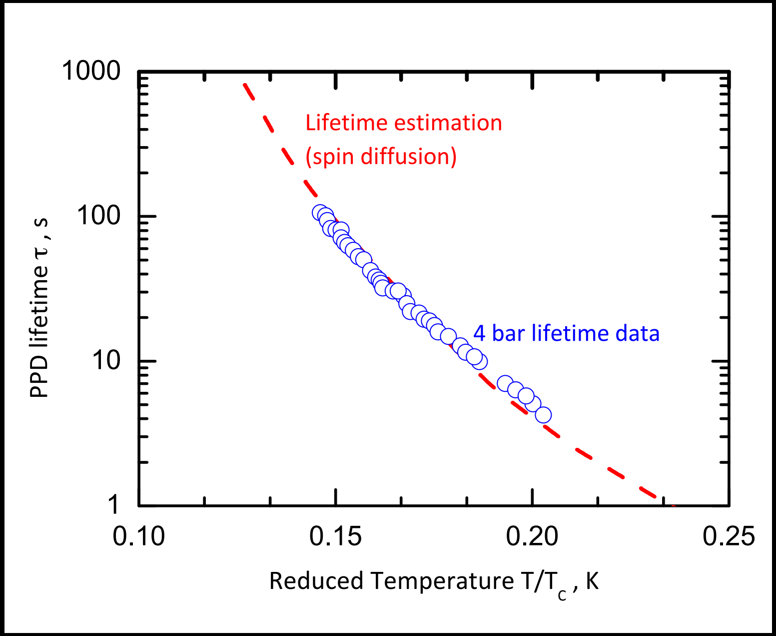
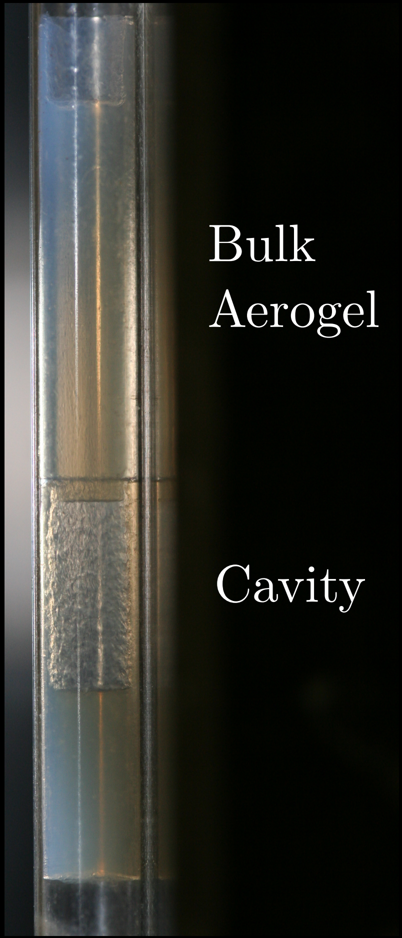
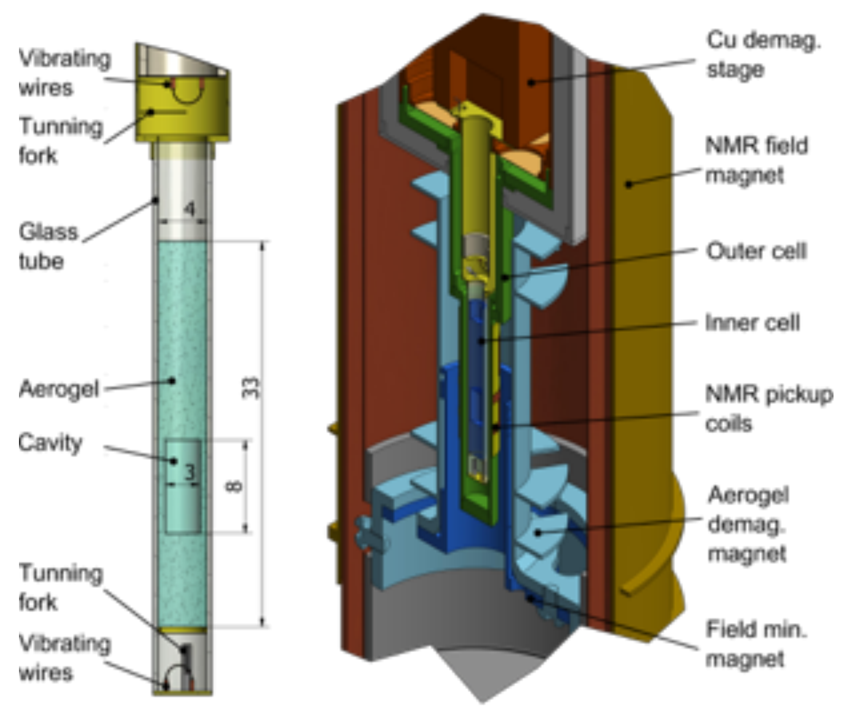




- demag the solid $^3$He layers which coat the aerogel strands
- enclosed cavity for experiments on bulk
- free decay of the Persistent Precessing Domain (PPD) may last several hours

# Demagnetisation of Solid $^3$He on Aerogel to Study Quasiparticle-Free Superfluid

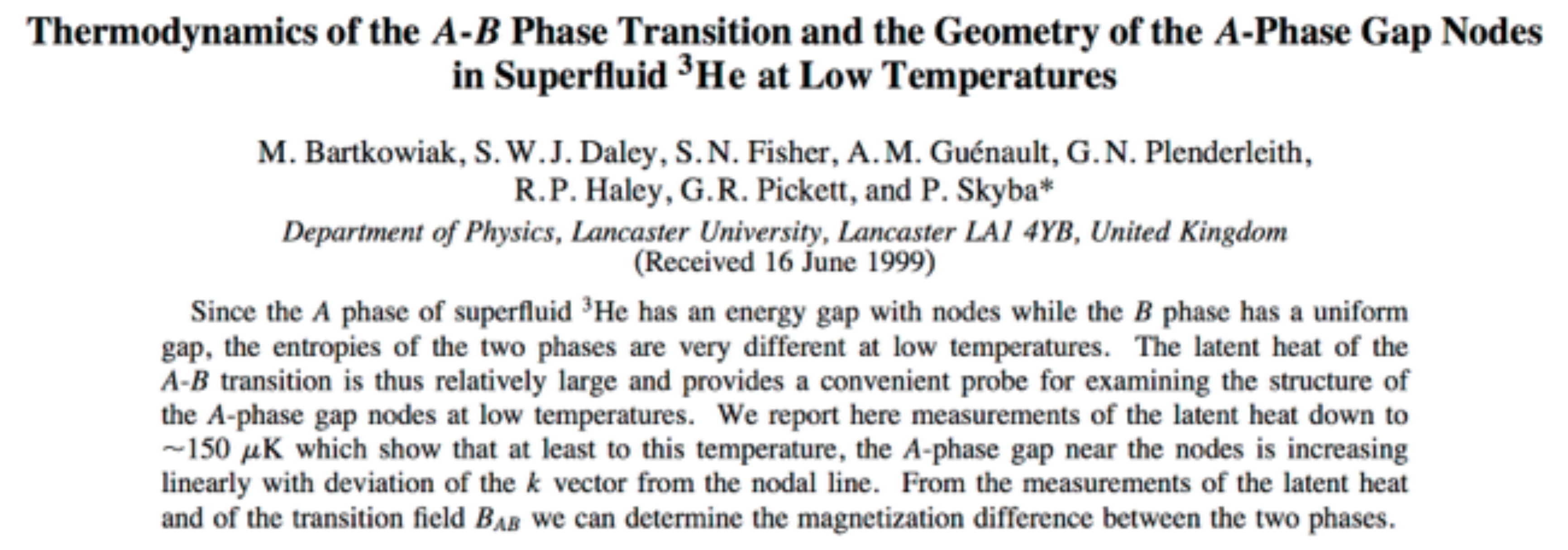




Good thermalisation within the aerogel

Boundary resistance at the bulk-aerogel interface?

Watch this space!

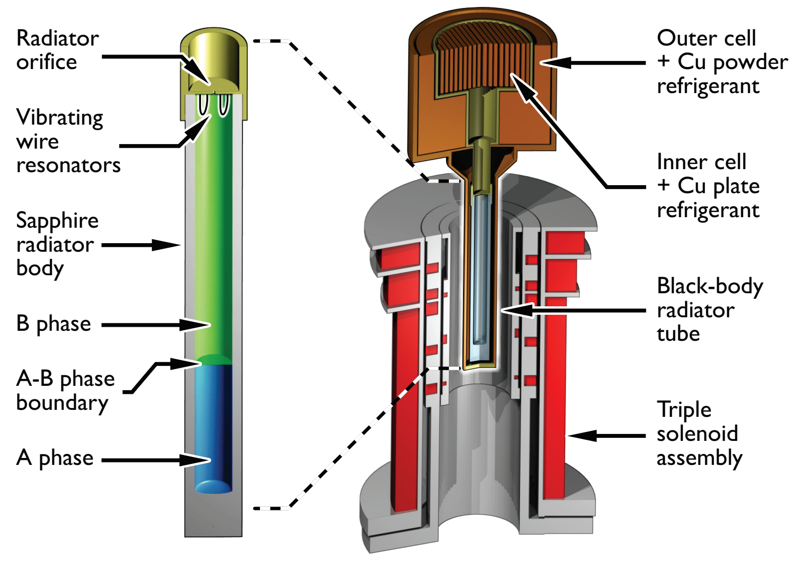


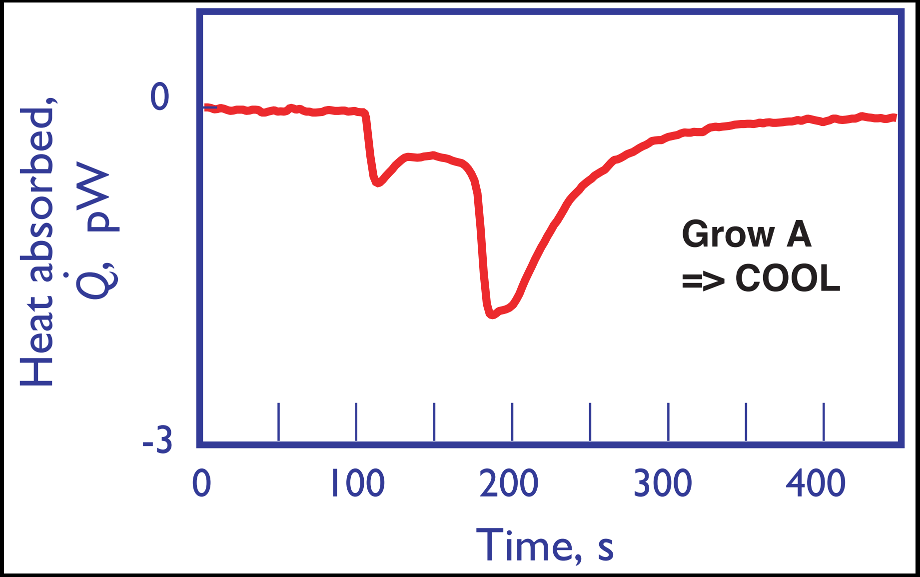
# Thermodynamics of the *A*-*B* Phase Transition and the Geometry of the *A*-Phase Gap Nodes in Superfluid $^3$He at Low Temperatures

M. Bartkowiak, S. W. J. Daley, S. N. Fisher, A. M. Guénault, G. N. Plenderleith,
R. P. Haley, G. R. Pickett, and P. Skyba*
*Department of Physics, Lancaster University, Lancaster LA1 4YB, United Kingdom*

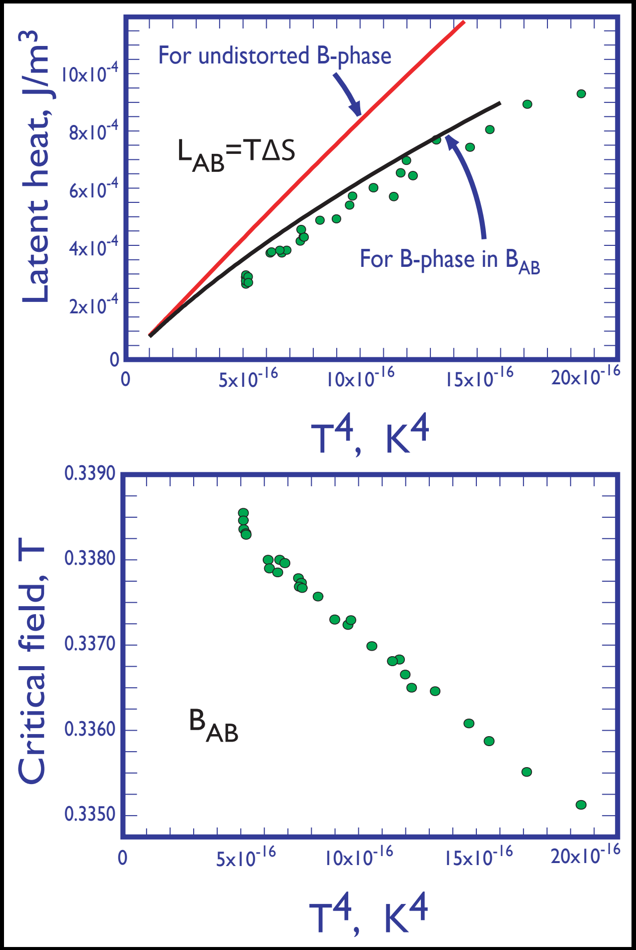
(Received 16 June 1999)

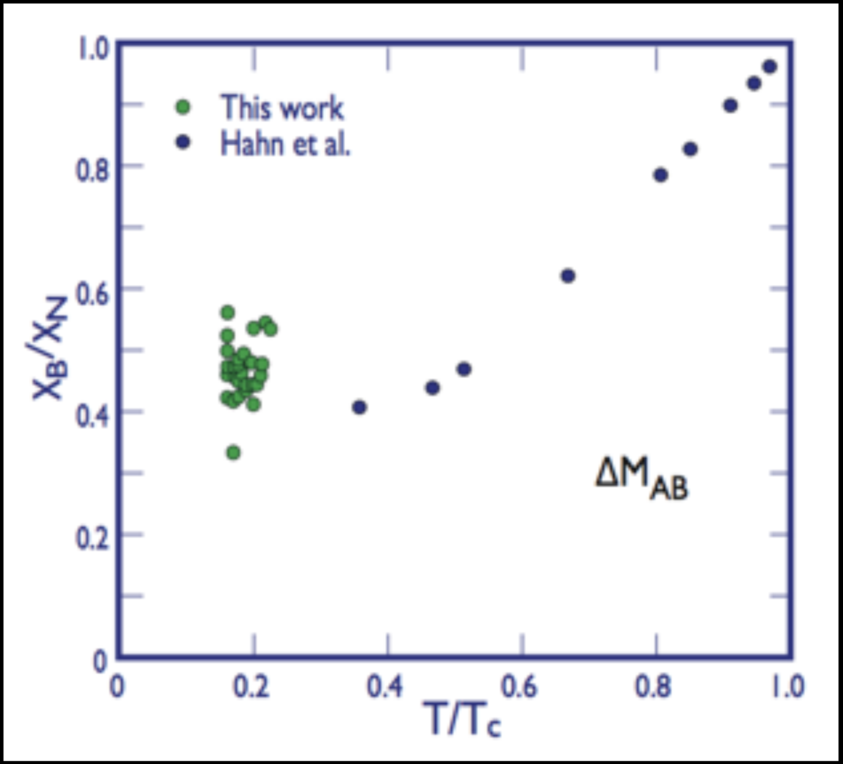
Since the *A* phase of superfluid $^3$He has an energy gap with nodes while the *B* phase has a uniform gap, the entropies of the two phases are very different at low temperatures. The latent heat of the *A*-*B* transition is thus relatively large and provides a convenient probe for examining the structure of the *A*-phase gap nodes at low temperatures. We report here measurements of the latent heat down to ~150 $\mu$K which show that at least to this temperature, the *A*-phase gap near the nodes is increasing linearly with deviation of the $k$ vector from the nodal line. From the measurements of the latent heat and of the transition field $B_{AB}$ we can determine the magnetization difference between the two phases.





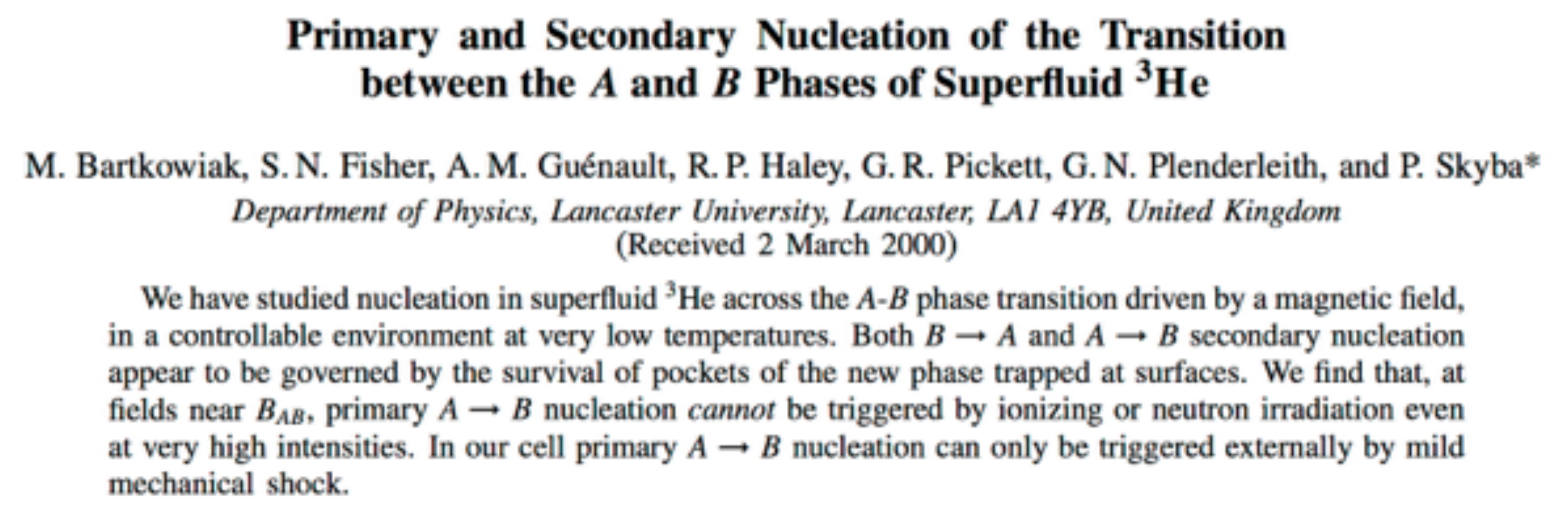
# Thermodynamics of the *A*-*B* Phase Transition and the Geometry of the *A*-Phase Gap Nodes in Superfluid $^3$He at Low Temperatures





Exemplar of 1st order phase transition

B phase field-distortion calculations work.
The A phase is ABM state



## Primary and Secondary Nucleation of the Transition between the *A* and *B* Phases of Superfluid $^3$He

M. Bartkowiak, S. N. Fisher, A. M. Guénault, R. P. Haley, G. R. Pickett, G. N. Plenderleith, and P. Skyba*
*Department of Physics, Lancaster University, Lancaster, LA1 4YB, United Kingdom*

(Received 2 March 2000)

We have studied nucleation in superfluid $^3$He across the $A$-$B$ phase transition driven by a magnetic field, in a controllable environment at very low temperatures. Both $B \rightarrow A$ and $A \rightarrow B$ secondary nucleation appear to be governed by the survival of pockets of the new phase trapped at surfaces. We find that, at fields near $B_{AB}$, primary $A \rightarrow B$ nucleation *cannot* be triggered by ionizing or neutron irradiation even at very high intensities. In our cell primary $A \rightarrow B$ nucleation can only be triggered externally by mild mechanical shock.

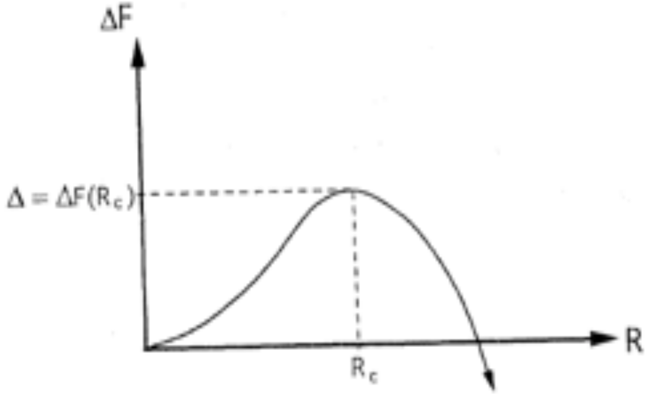


FIG. 3. Schematic of the total energy of a bubble of $B$ phase in supercooled $A$ phase as a function of the radius of the bubble. The energy increases with increasing bubble size for $R < R_c$, due to the surface tension, and then decreases for $R > R_c$.

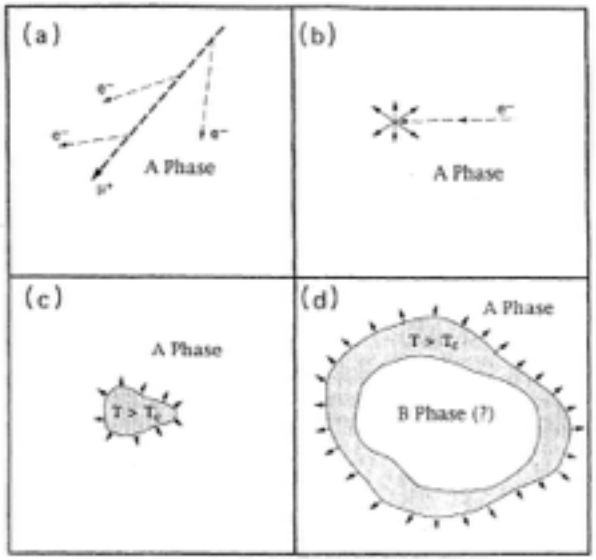
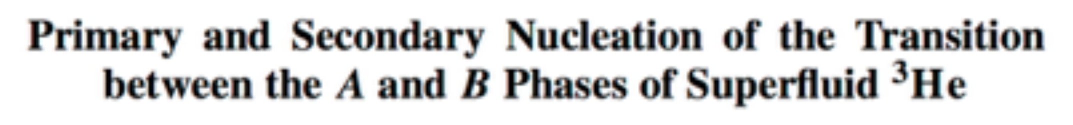
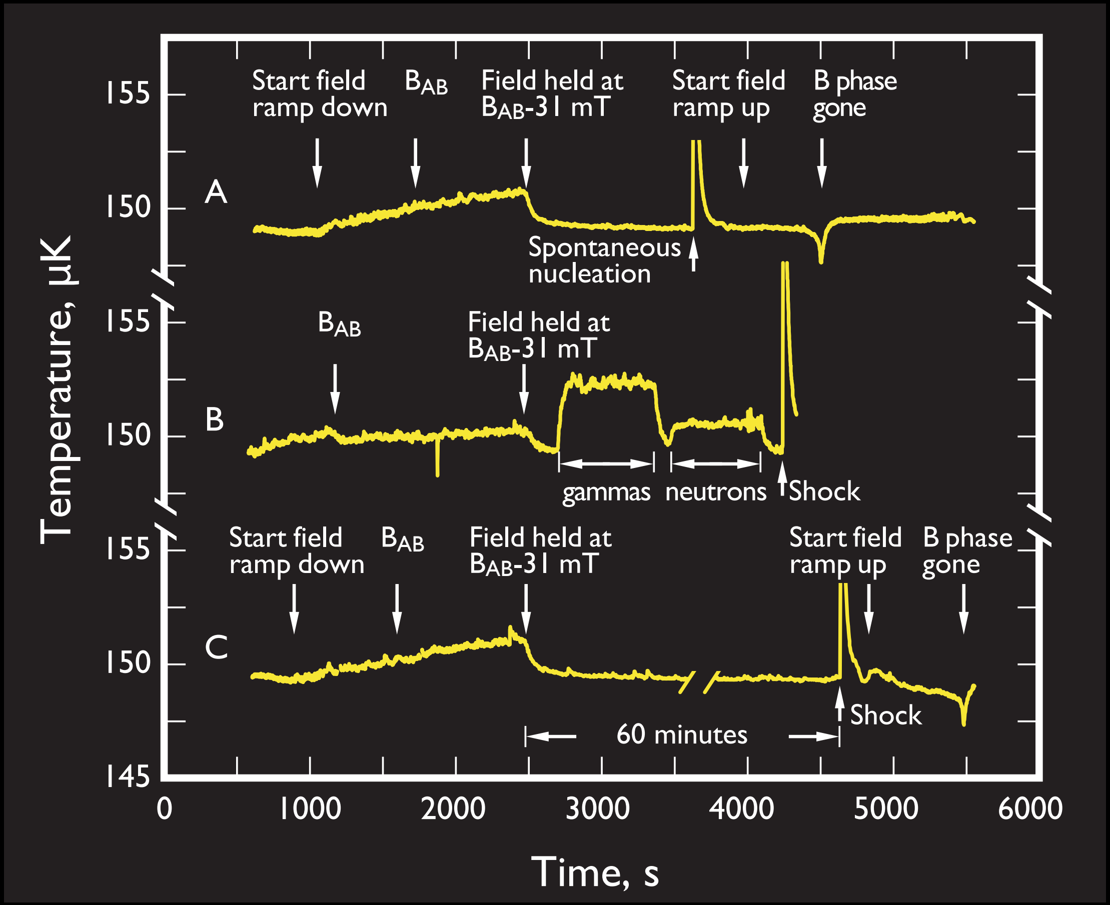


FIG. 4. Schematic representation of the baked Alaska process

**Osheroff and Schiffer, Rev. Mod. Phys. 67, on Leggett's "Baked Alaska"**
**Bunkov and Timofeevskaya, PRL 80, on Kibble-Zurek scenario**



# Primary and Secondary Nucleation of the Transition between the *A* and *B* Phases of Superfluid $^3$He



Primary nucleation triggered by mechanical shock but not by radiation.

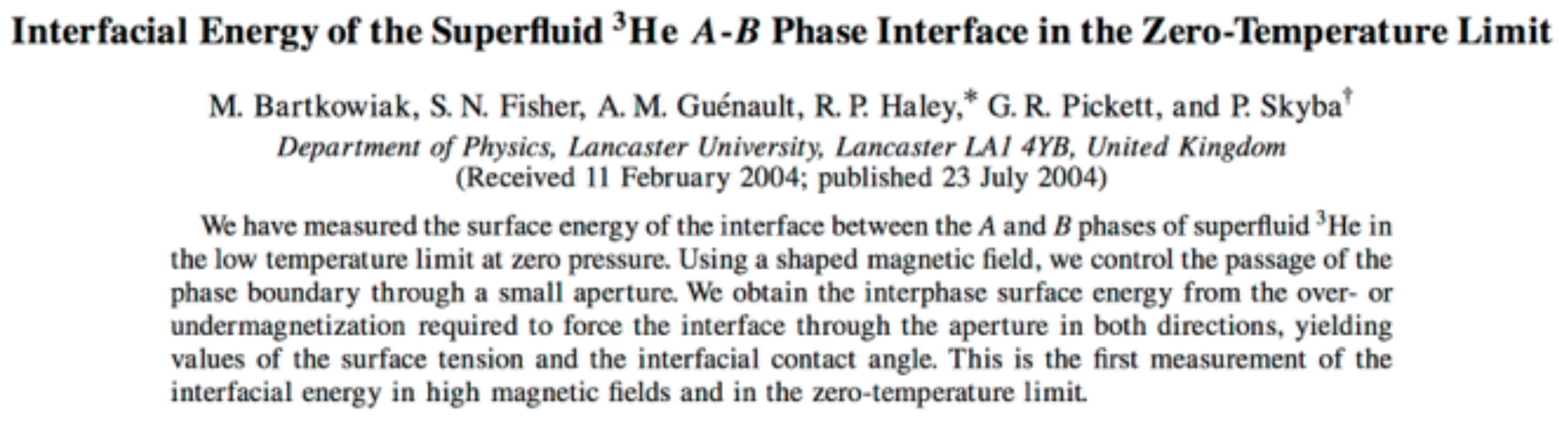
Secondary nucleation behaviour has a memory effect that also depends on the direction.

"3He's dirty secret"

- Henry Tye

Resonant tunnelling between quantum vacuum states?

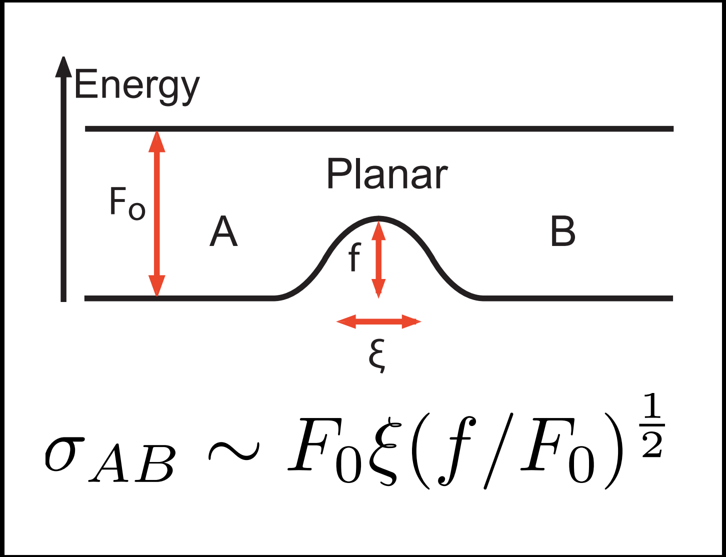
Experiments difficult (but also easy) - potentially very rewarding



**Interfacial Energy of the Superfluid $^3$He *A*-*B* Phase Interface in the Zero-Temperature Limit**

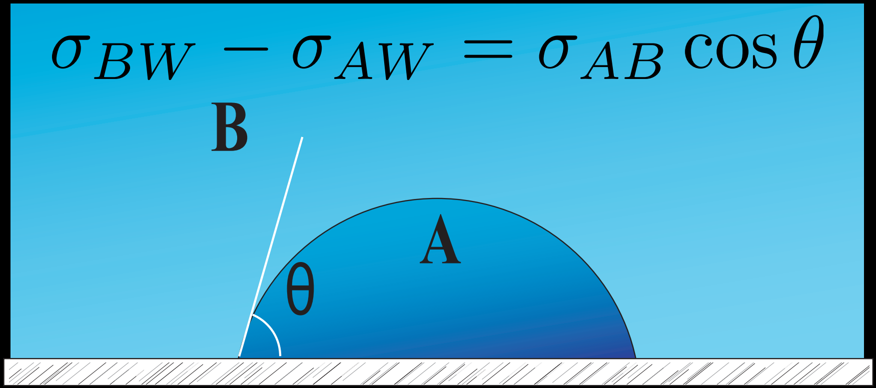
M. Bartkowiak, S. N. Fisher, A. M. Guénault, R. P. Haley,* G. R. Pickett, and P. Skyba†
*Department of Physics, Lancaster University, Lancaster LA1 4YB, United Kingdom*
(Received 11 February 2004; published 23 July 2004)

We have measured the surface energy of the interface between the *A* and *B* phases of superfluid $^3$He in the low temperature limit at zero pressure. Using a shaped magnetic field, we control the passage of the phase boundary through a small aperture. We obtain the interphase surface energy from the over- or undermagnetization required to force the interface through the aperture in both directions, yielding values of the surface tension and the interfacial contact angle. This is the first measurement of the interfacial energy in high magnetic fields and in the zero-temperature limit.



$$\sigma_{AB} \sim F_0 \xi (f/F_0)^{\frac{1}{2}}$$

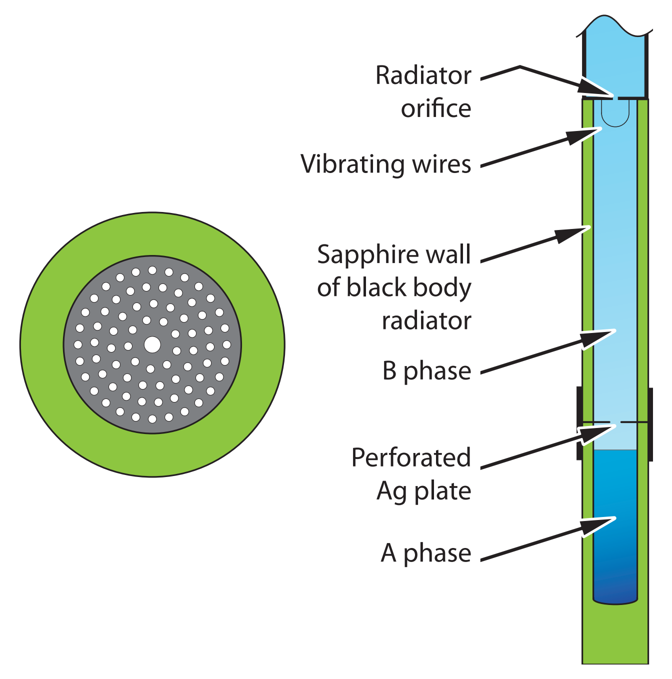
Order parameter transforms smoothly from A to B
(via planar?)

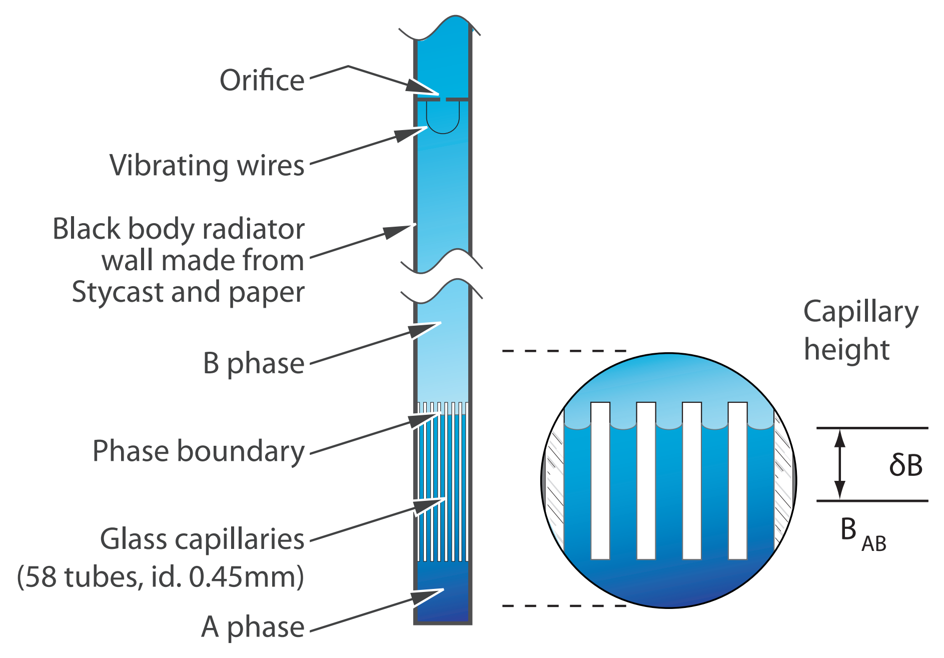


$$\sigma_{BW} - \sigma_{AW} = \sigma_{AB} \cos\theta$$

Surface tension and wetting

# Interfacial Energy of the Superfluid $^3$He *A*-*B* Phase Interface in the Zero-Temperature Limit





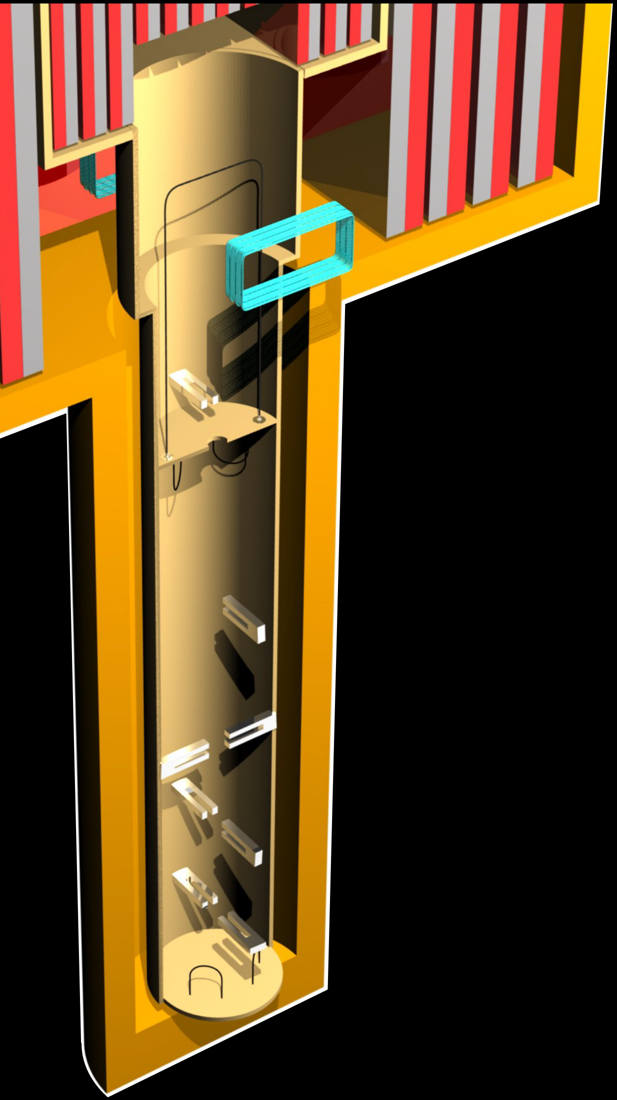
$$\sigma_{AB} \approx 0.45\xi F_0$$

$$\theta \approx 68^\circ$$

“Pop” the interface through holes and measure it climbing up the walls

Important thermodynamic quantity - fairly good agreement with “first principles” calculations

(Doesn’t solve the nucleation problem)



# Some open questions…

Interface order parameter?
- transport through and within

Dynamic textures and orbital motion
- boundary conditions
- friction
- tuneable effective mass

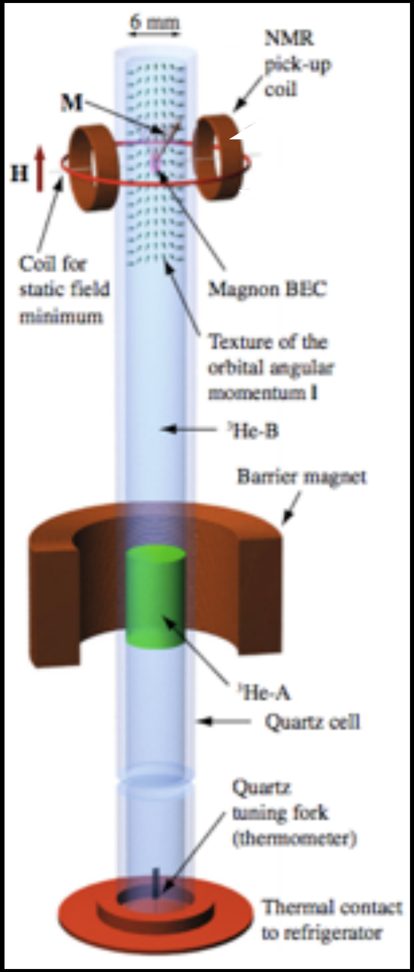
Ripplons?

High field distortion
- spin filter?

Vortices/defects and the interface
- instabilities, event horizons

3D control of transition/interface

Interfaces in 2D confinement



Eltsov et al,
Aalto, Finland
AB in rotation

Lancaster University

Ultra Low Temperature

Lancaster Quantum Technology Centre

EPSRC
Engineering and Physical Sciences Research Council

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Garfield Weston
FOUNDATION

THE WOLFSON FOUNDATION

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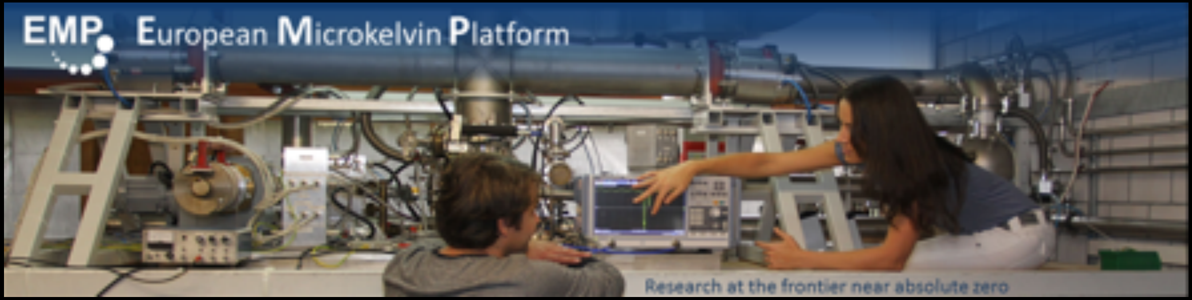
THE ROYAL SOCIETY

The Leverhulme Trust

Innovate UK
Technology Strategy Board

Cosmology
Condensed Matter
COSLAB
Particle Physics

EMP European Microkelvin Platform



Research at the frontier near absolute zero

welcome to the
European Microkelvin Collaboration

SEVENTH FRAMEWORK PROGRAMME

European Commission

Lancaster University

Ultra Low Temperature

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