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CryoUsers Conference 2024, The University of Leeds, UK

Can a tiny droplet of quantum fluid stop up-hill flowing liquid?

Oleg Kirichek, ISIS neutron and muon source, STFC, UKRI

40 Years of ISIS Neutron and Muon Source

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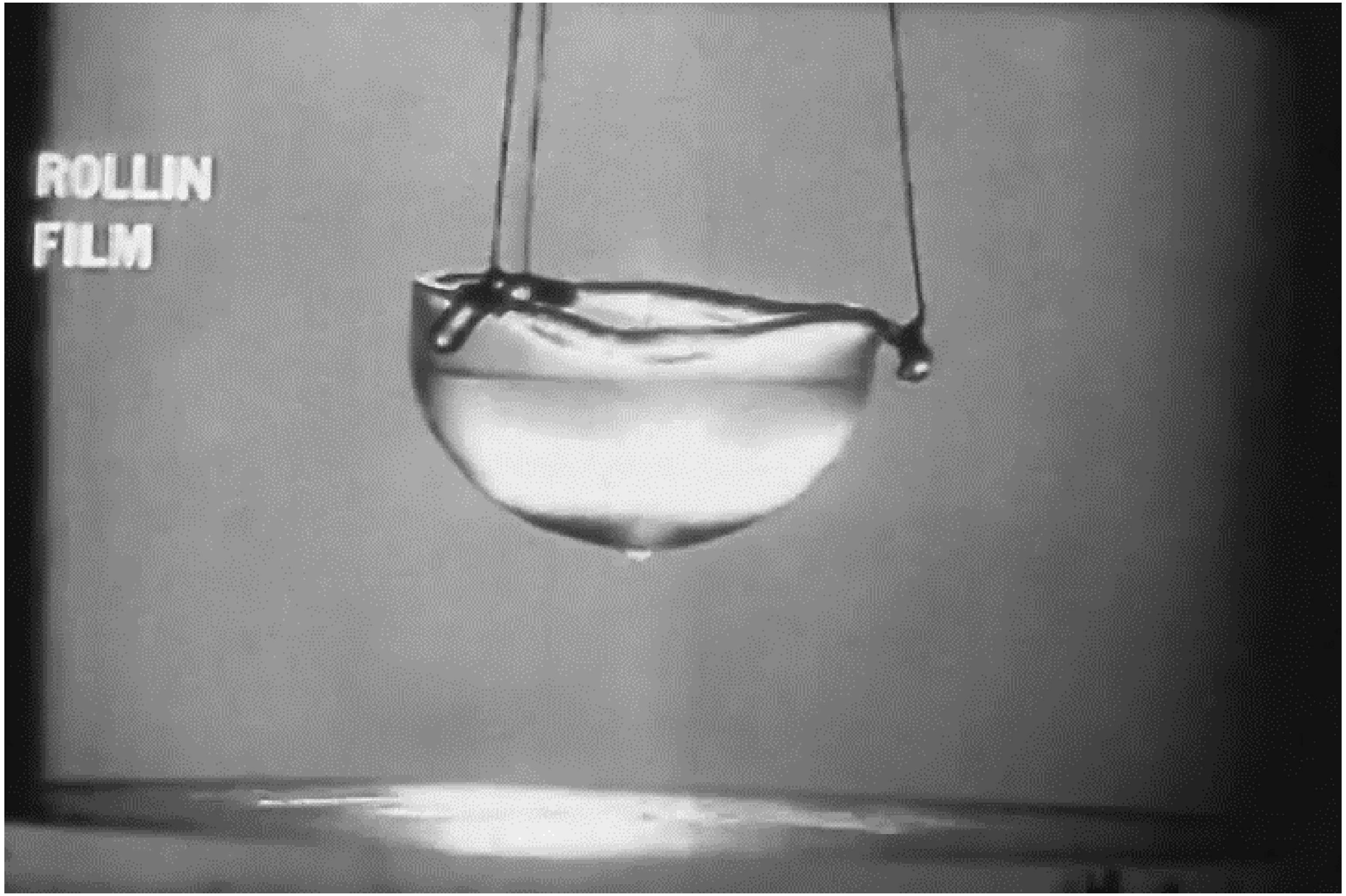
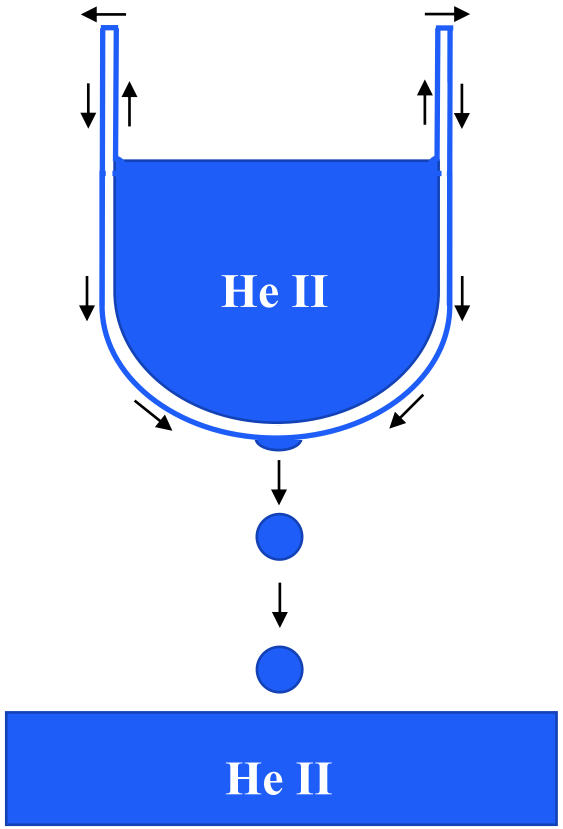
In mediaeval times the effect of ***fluids flowing uphill*** against gravity was considered a miracle, for example as one of the ***Seven Wonders of Fore Abbey*** in 7^{th} century, Ireland.



In the quantum world superfluid helium can defy gravity and is able to climb out of any container in a thin film that moves with such a pace that the container is drained in minutes.

Rollin, B. V. & Simon, F.
On the "film" phenomenon of liquid helium II.
Physica **6**, 219–230 (1939)
Clarendon Laboratory, Oxford University

From paper's abstract:
"It is concluded from the experiment that liquid He II "creeps out" of the container in the form of a film…"

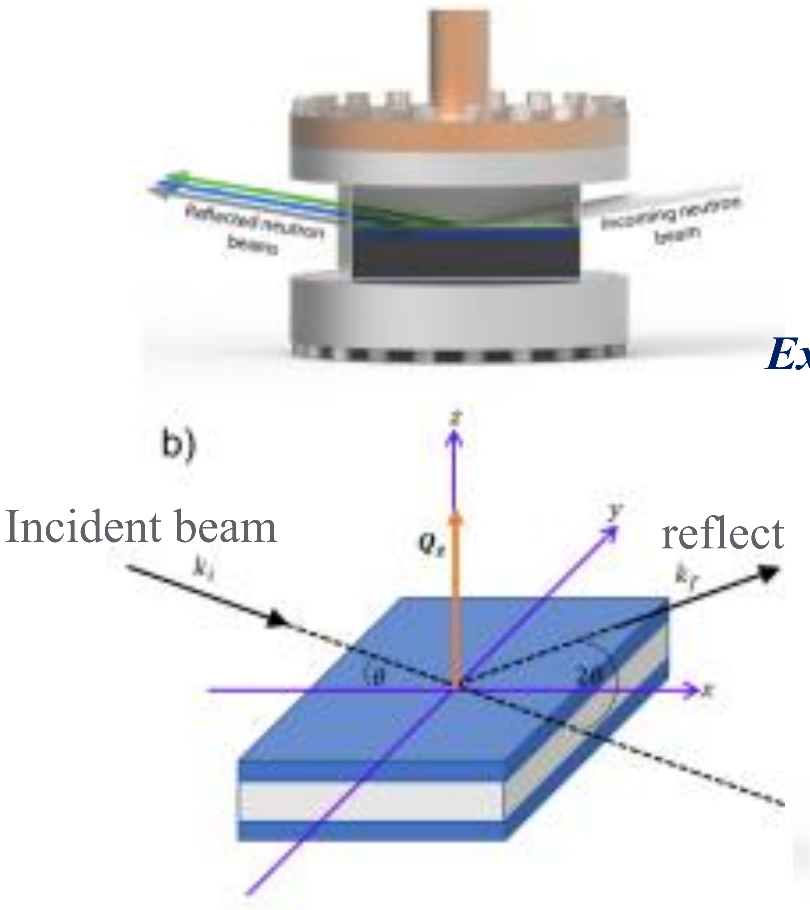


Superfluid helium

The ***superfluid transition*** in ***^4He*** occurs when liquid helium is cooled below ***2.17 K***.

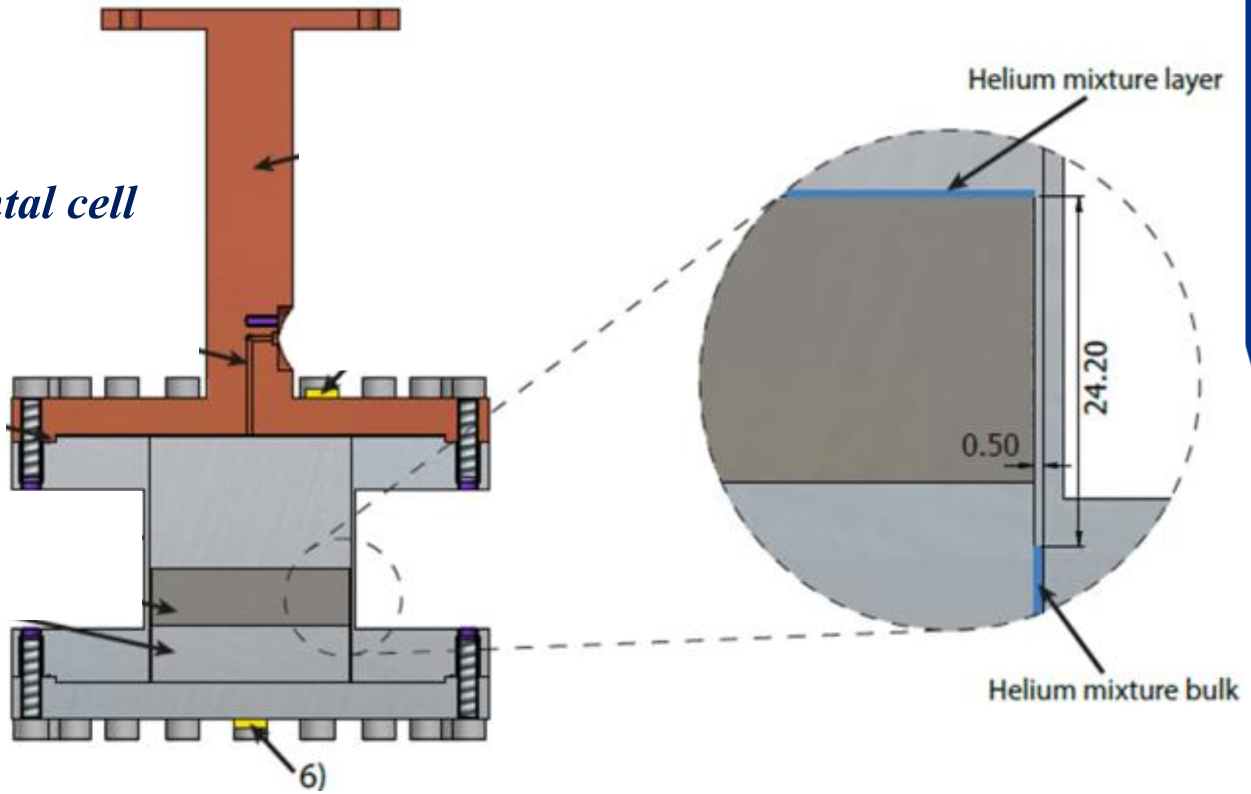
- Superfluid liquid ***^4He*** consists of ***superfluid*** and ***normal components***.
- The ***superfluid component*** has ***zero viscosity*** and zero entropy, therefore flows without dissipation.
- The ***normal component*** carries the heat and can produce a high velocity flow which leads to very ***high thermal conductivity***.

Superfluid helium film is extremely elusive!



Geometry of the cell in respect to neutron beam

Experimental cell



The distance between the ***bulk helium surface*** at the bottom of the cell and the ***surface of silicon block*** is maintained at ***2.42 cm.***

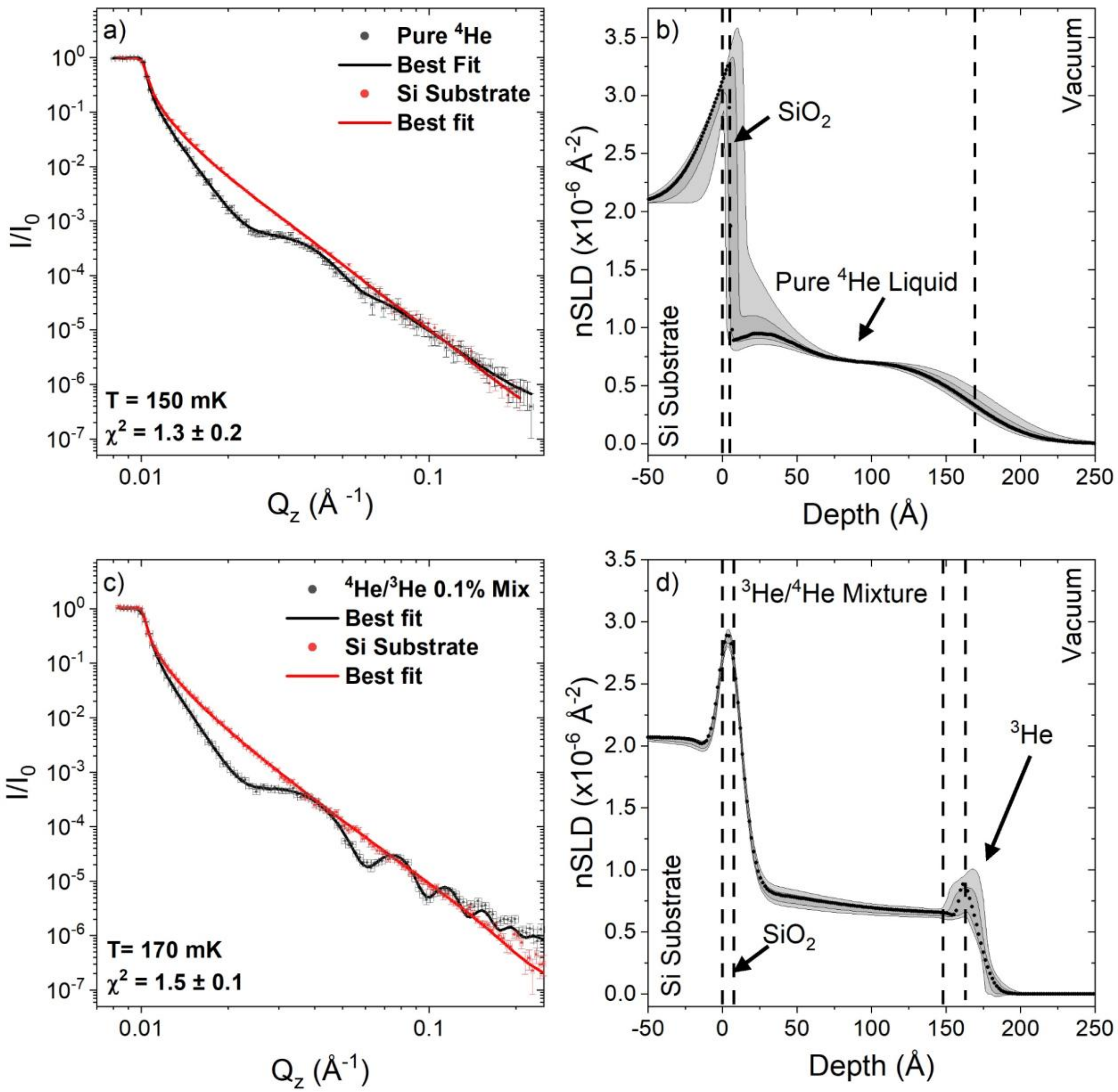
The He film thickness is ***160 Å***

Experimental set-up

POLREF block house

E-18 Cryogen-free
Dilution Refrigerator

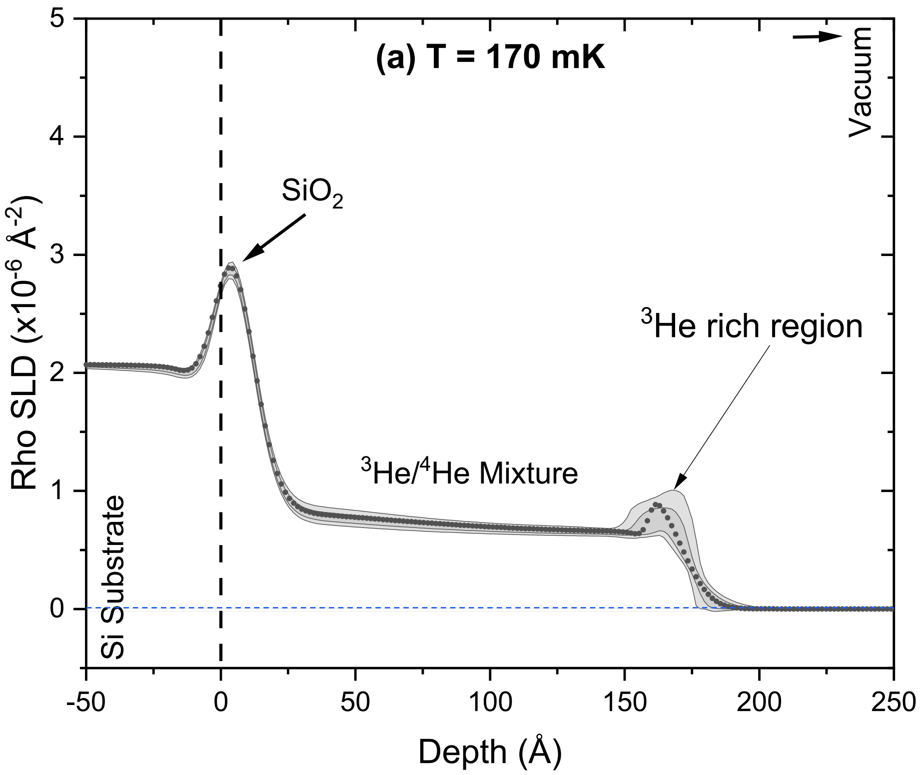
Neutron reflectivity curves. *Neutron scattering density profiles.*



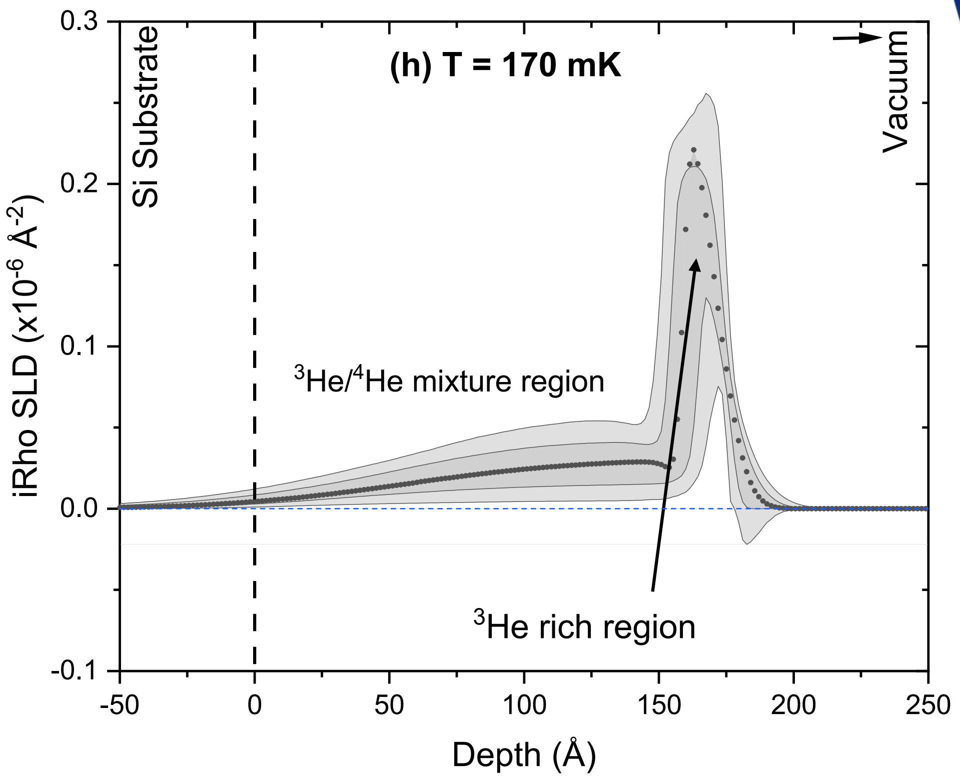
The grey region represents the Bayesian confidence interval.

^{3}He/^{4}He mixture film

Neutron scattering density profile



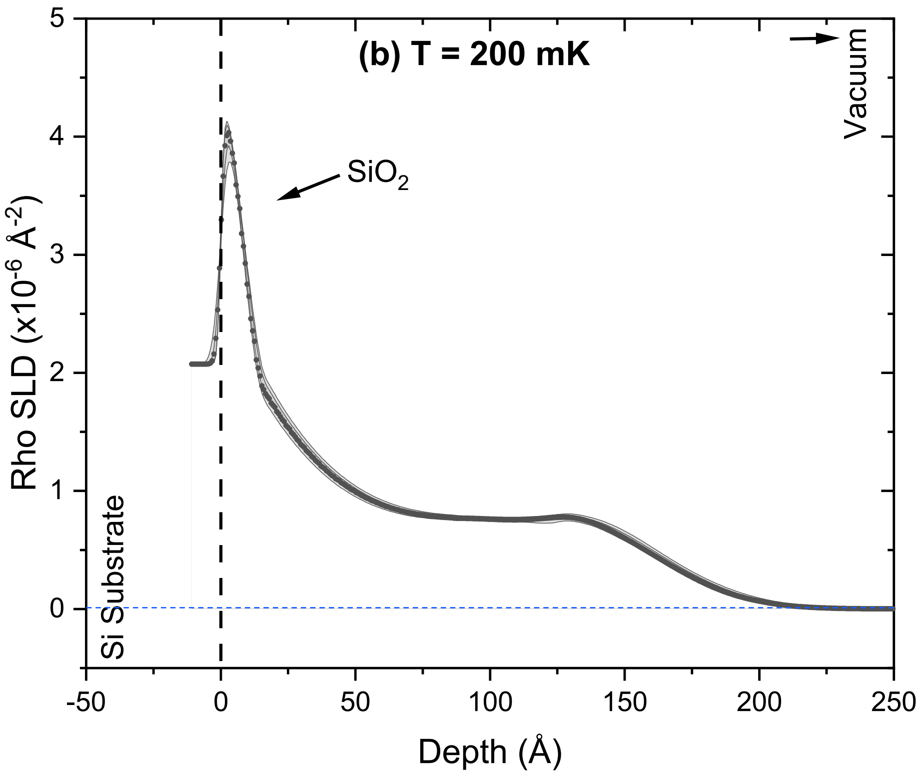
Neutron adsorption profile



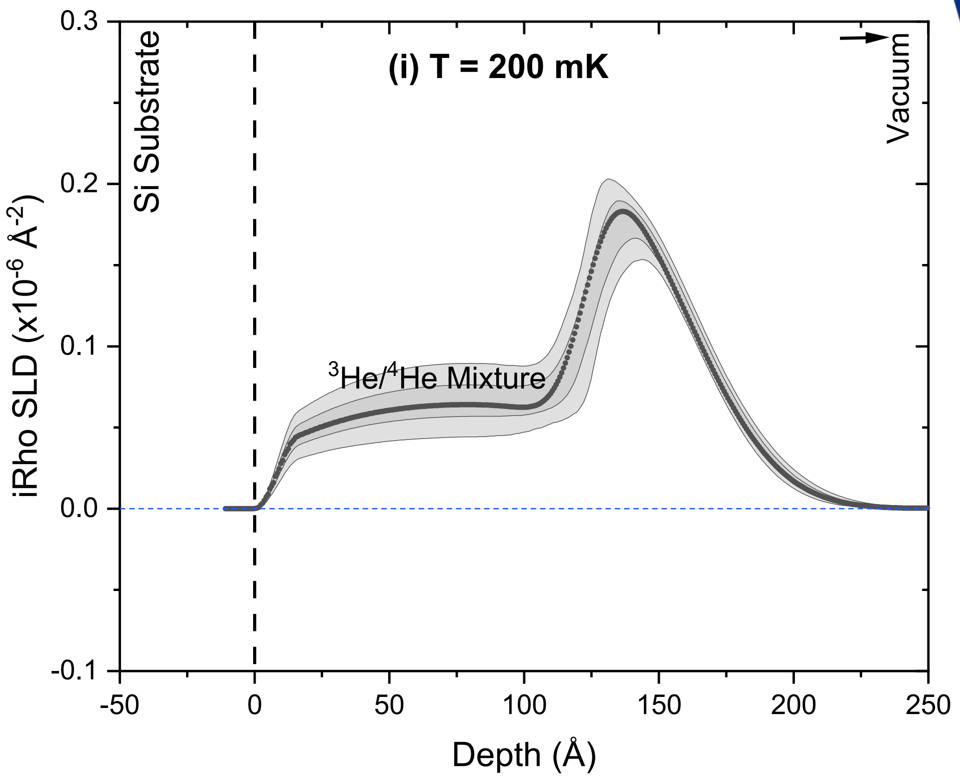
In the ^{3}He/ ^{4}He mixture film almost all adsorption comes from neutron scattering from ^{3}He atoms, therefore ***right figure represent the distribution of ^{3}He atoms inside the film***.

$^3He/^4He$ mixture film

Neutron scattering density profile

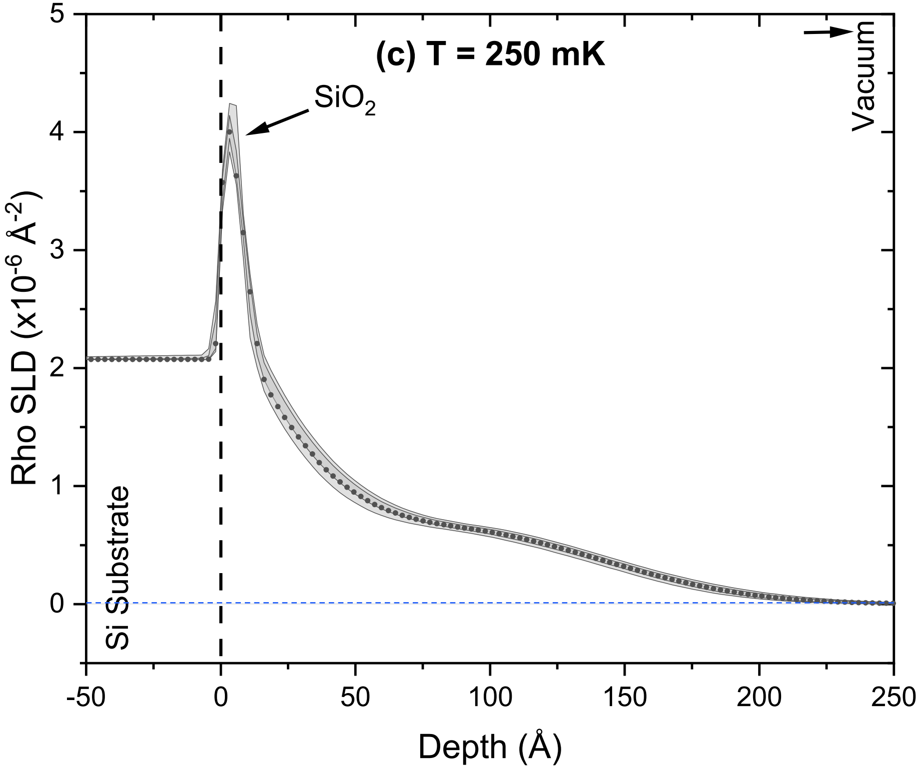


Neutron adsorption profile

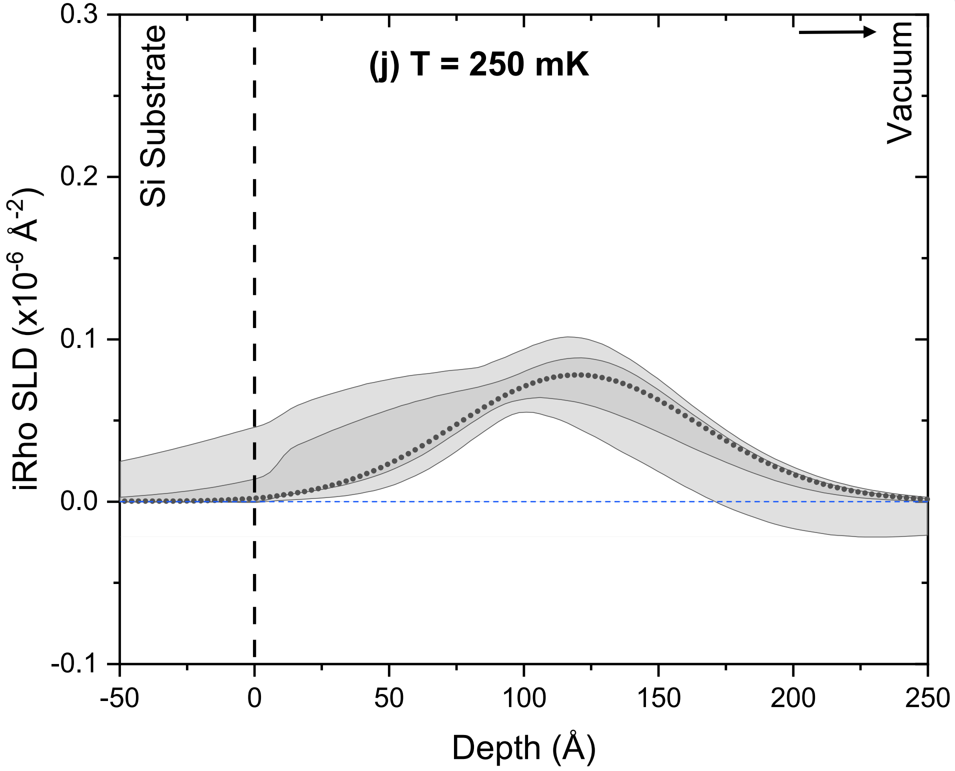


$^3He/^4He$ mixture film

Neutron scattering density profile

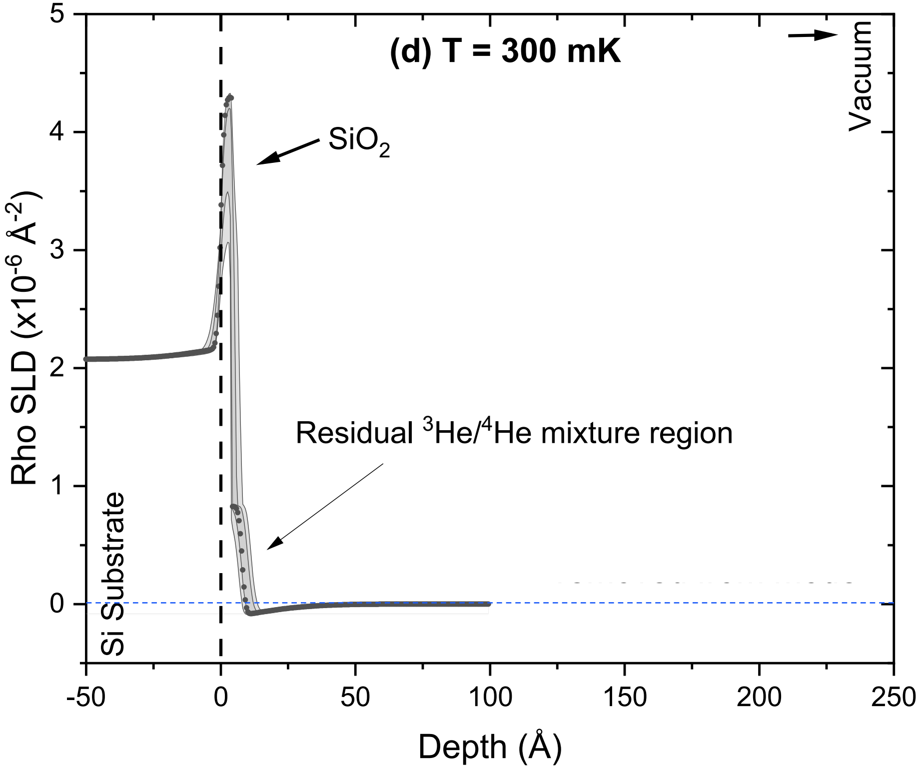


Neutron adsorption profile

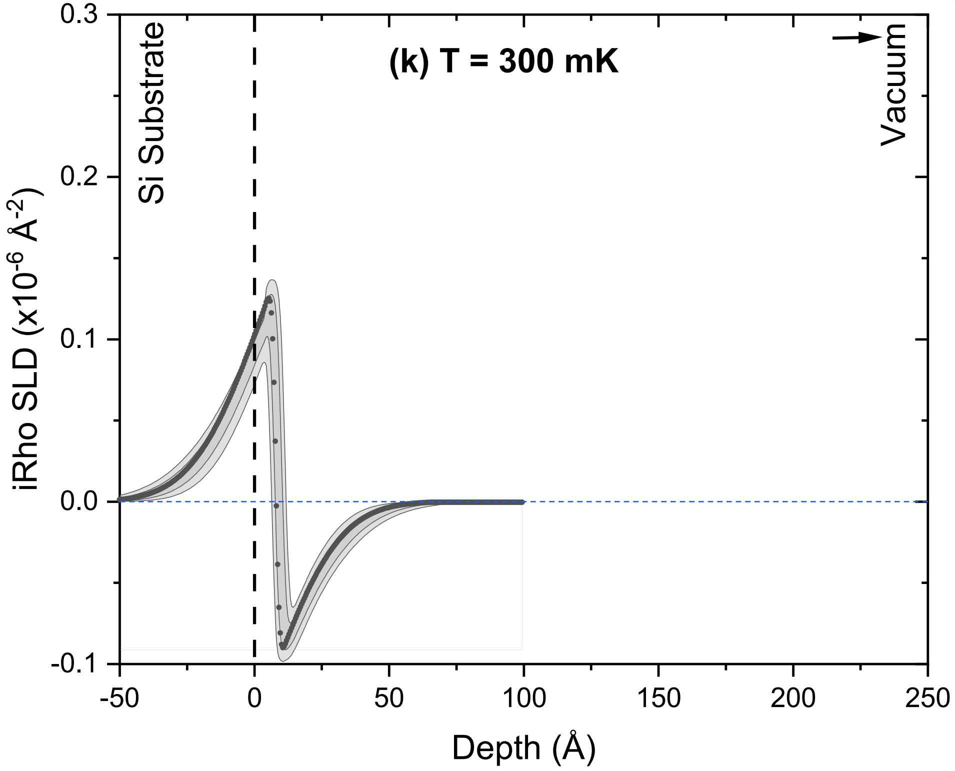


$^3He/^4He$ mixture film

Neutron scattering density profile



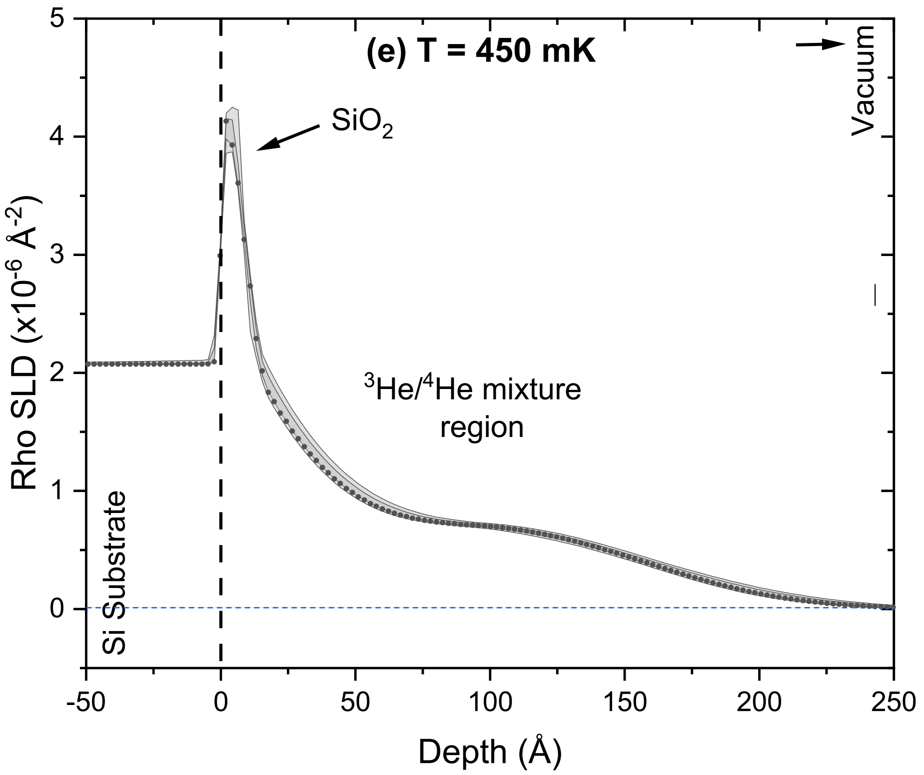
Neutron adsorption profile



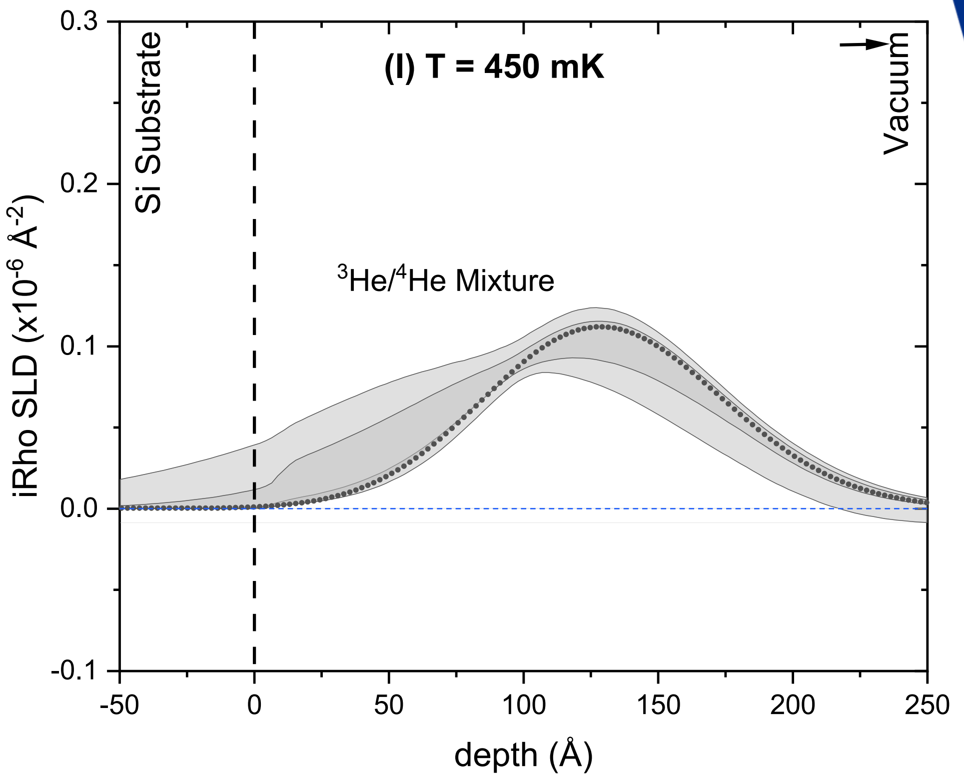
Up-hill flowing liquid is stopped!

$^3He/^4He$ mixture film

Neutron scattering density profile

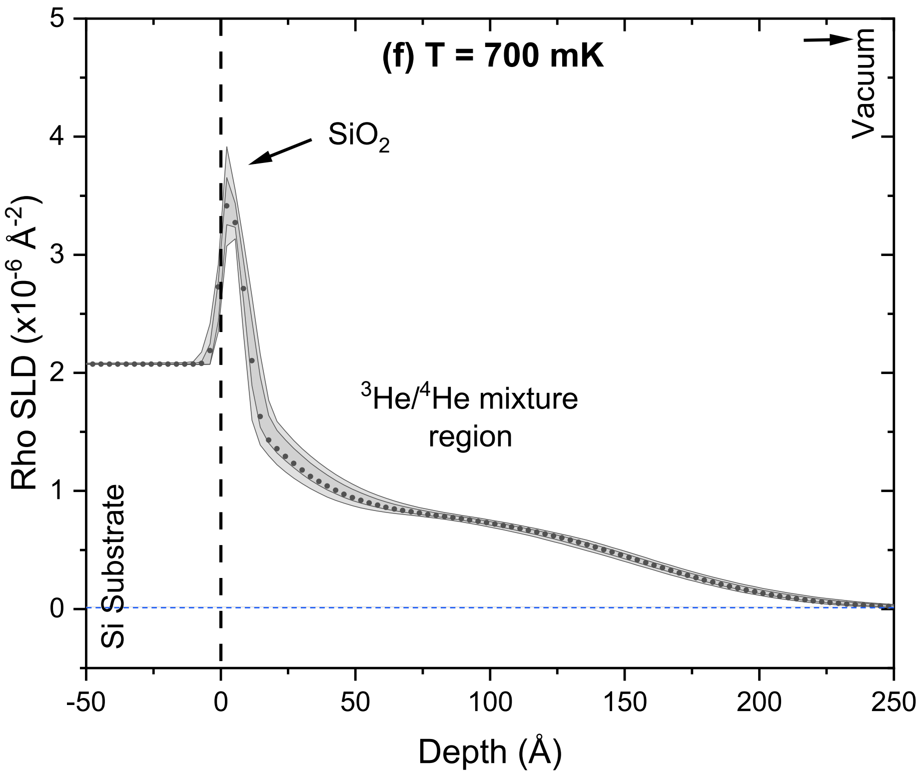


Neutron adsorption profile

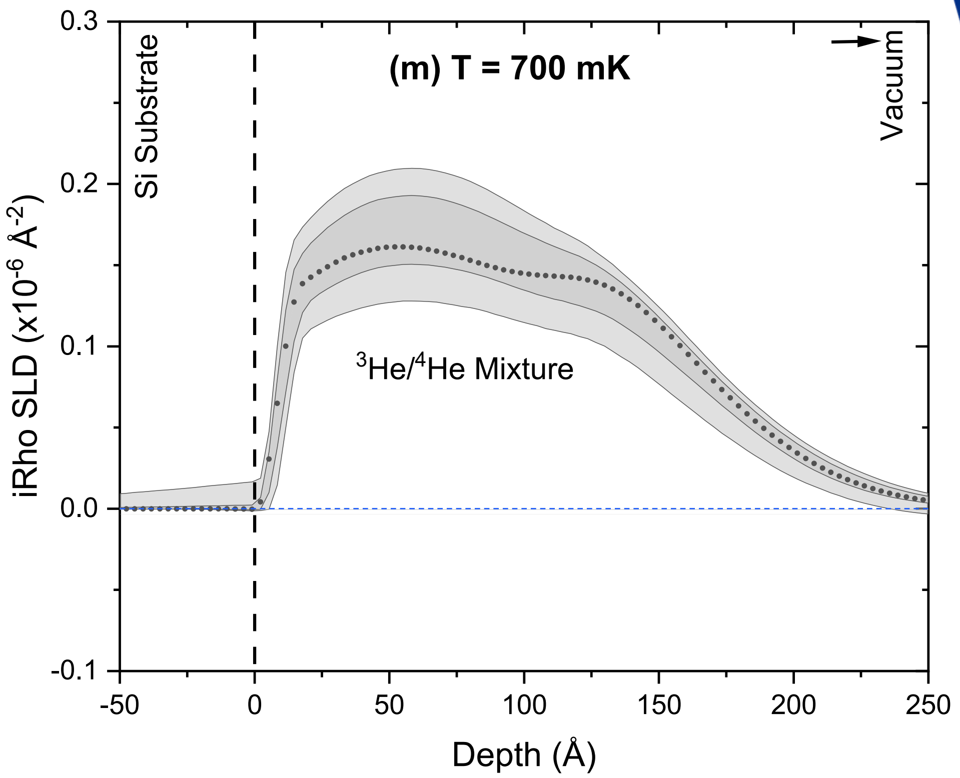


$^3He/^4He$ mixture film

Neutron scattering density profile

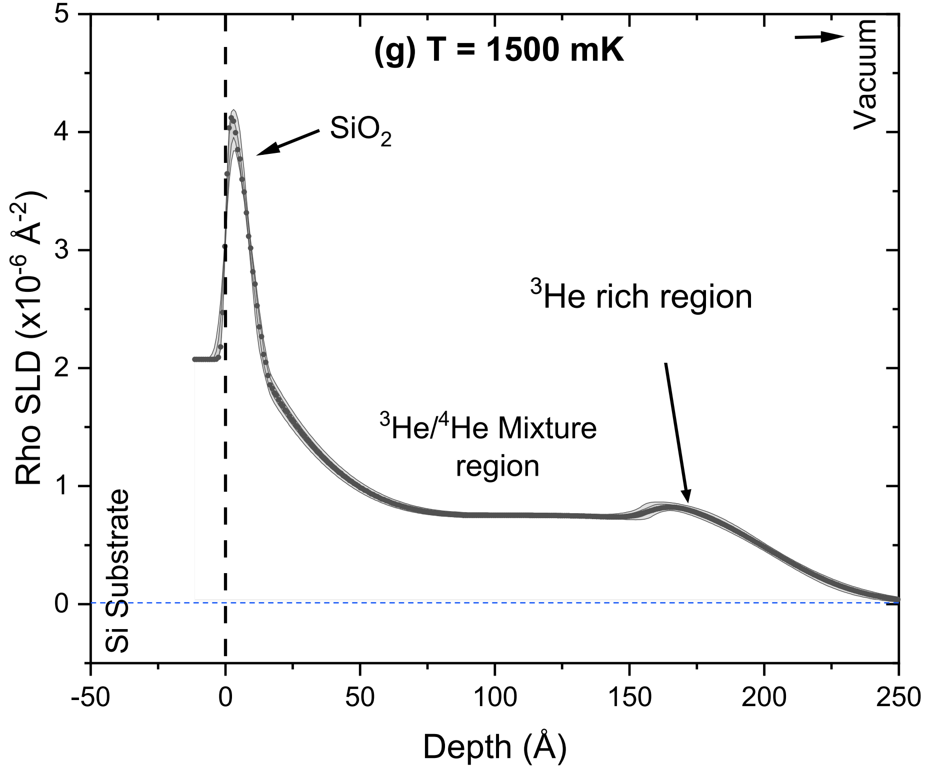


Neutron adsorption profile

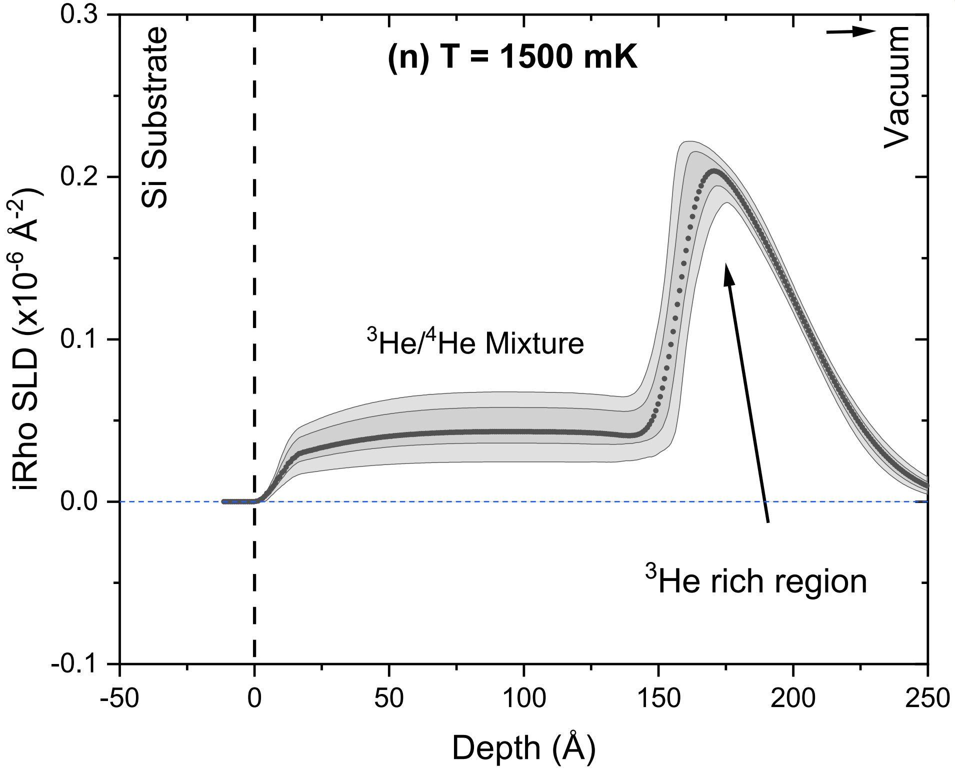


$^3He/^4He$ mixture film

Neutron scattering density profile

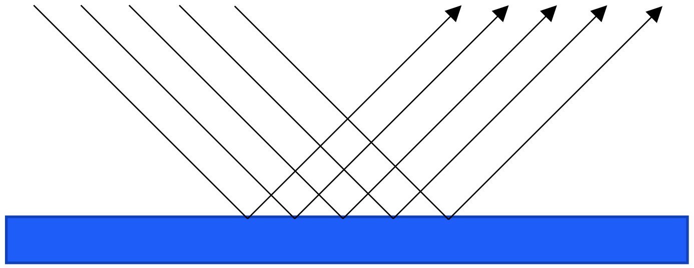


Neutron adsorption profile



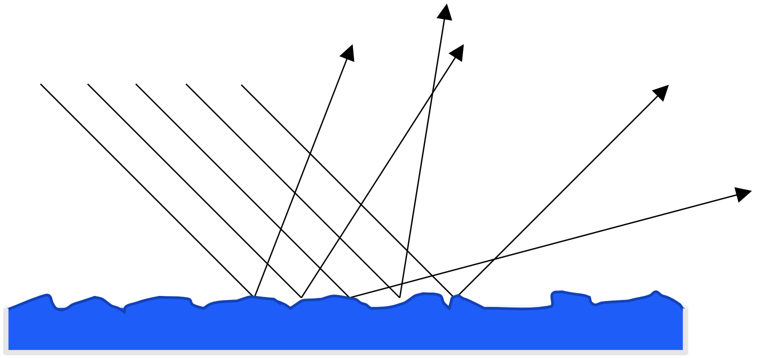
What is Reflectivity?

Specular reflection (when the angle of incidence equals the angle of reflection):



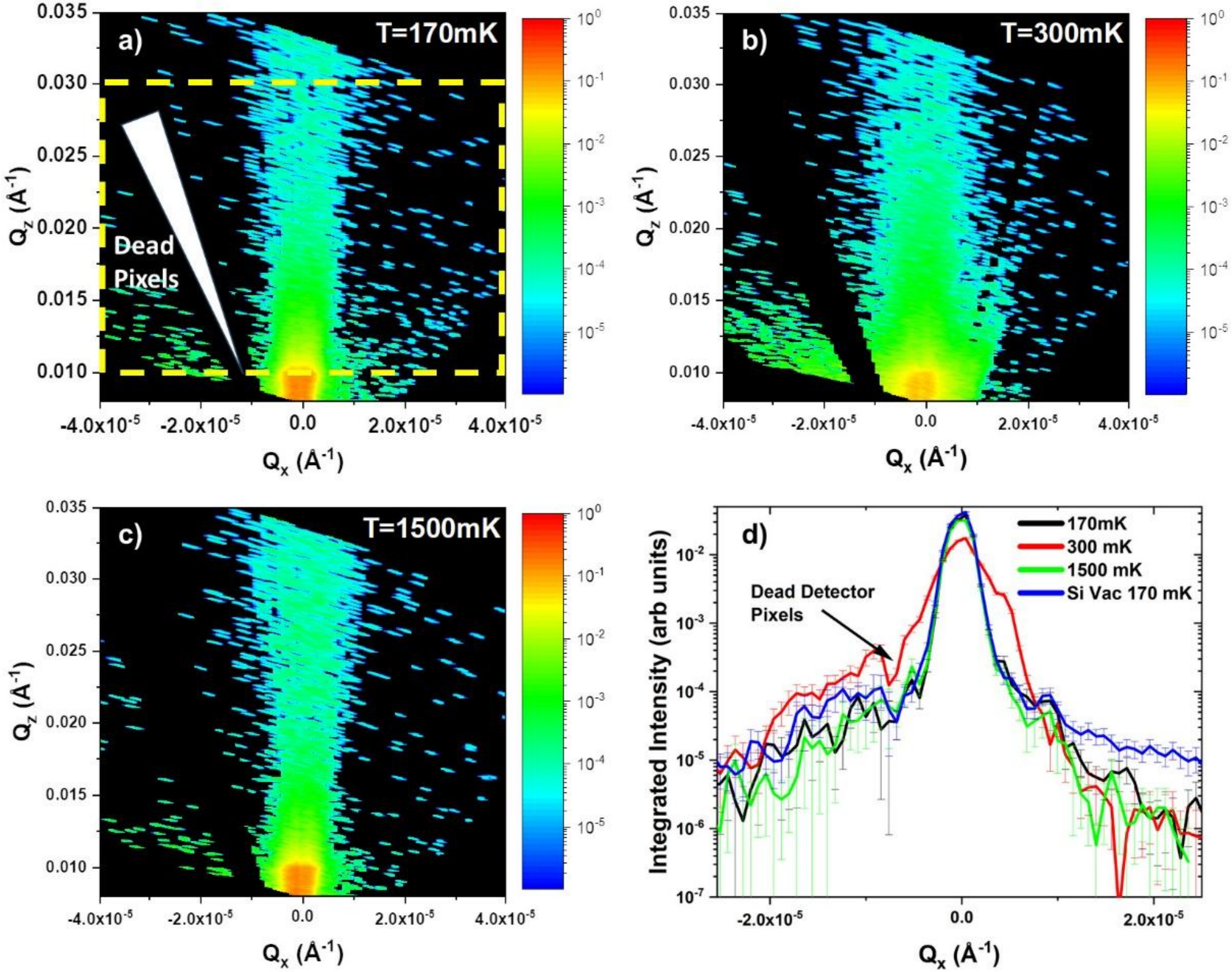
$$\alpha_i = \alpha_r$$

Off-Specular or diffuse reflection:



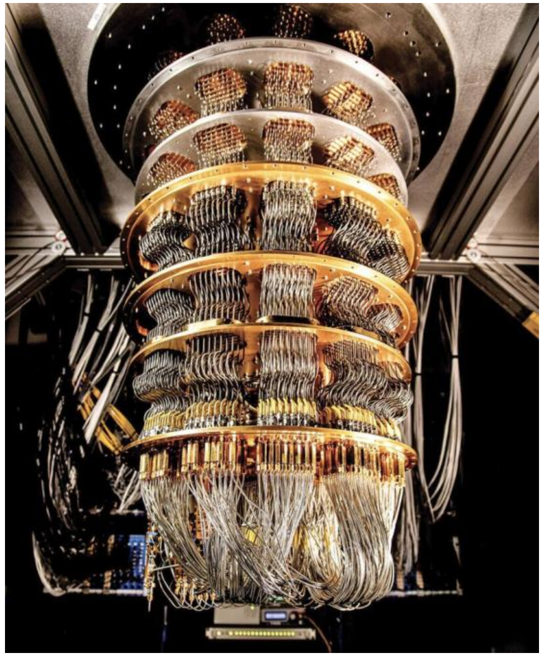
$$\alpha_i \neq \alpha_r$$

Specular and off-specular neutron scattering from the 3He/4He mixture.

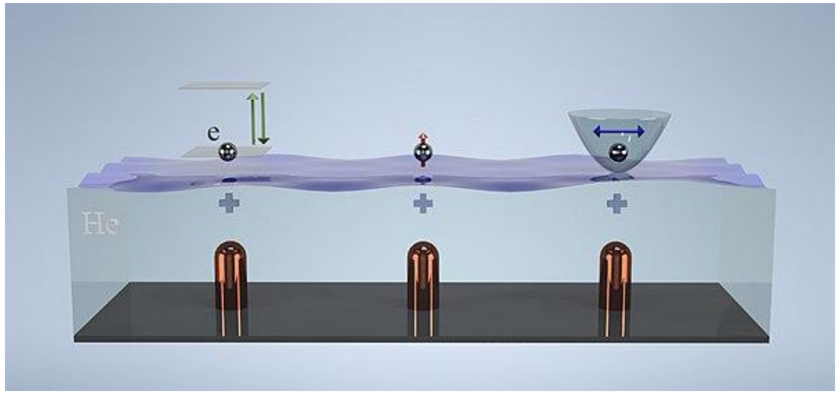


pseudo rocking curves

Possible applications



Superfluid ***helium film*** is a limiting factor for performance of ***powerful dilution refrigerators*** which are used for cooling ***quantum computers.***



Recent realisation of ***qubits based on electron-on-helium*** demonstrated a record high ***decoherence time***. Understanding of helium film properties is a key factor for development of these qubits.

In summary

- We presented the first study of pure ^4He and ^3He/ ^4He mixture films using neutron reflection, in the temperature range of 150 mK to 1.5K.
- Thanks to the exceptional sensitivity and precision of this technique, we have observed a phase-separated ^3He/ ^4He mixture film at 170 mK.
- We have been able to watch the gradual dissolution of ^3He top layer into ^4He with increasing temperature.
- We have observed anomaly in the film behaviour around 300 mK that could be caused by a phase transition.
- We also discover an unexpected restoration of the layered structure at 1.5 K.

communications physics

Article

https://doi.org/10.1038/s42005-024-01683-w

Density profile of ^{3}He in a nanoscale ^{3}He-^{4}He superfluid film determined by neutron scattering

Check for updates

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For decades, superfluid helium has attracted the interest of the scientific community as an extremely pure realisation of a quantum liquid, only accessible at temperatures close to absolute zero. Previously, helium films have only been observed directly using X-rays. However, this method is limited to temperatures above 1 K due to the high levels of energy deposition, and it also suffers from an inability to distinguish between helium isotopes. Here we show that a ^{3}He layer on top of a phase separated mixture film at 170 mK gradually dissolves into the ^{4}He with increasing temperature. We also observe an anomaly in film behaviour near 300 mK and unexpected restoration of the layered structure at 1.5 K which is consistent with a re-entrant phase transition leading to the suppression of superfluidity in the film near 300 mK. Our successful application of neutron scattering to study helium films at ultra-low temperatures opens up new possibilities for future research.

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All 3 Sections of ISIS Sample Environment group!

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