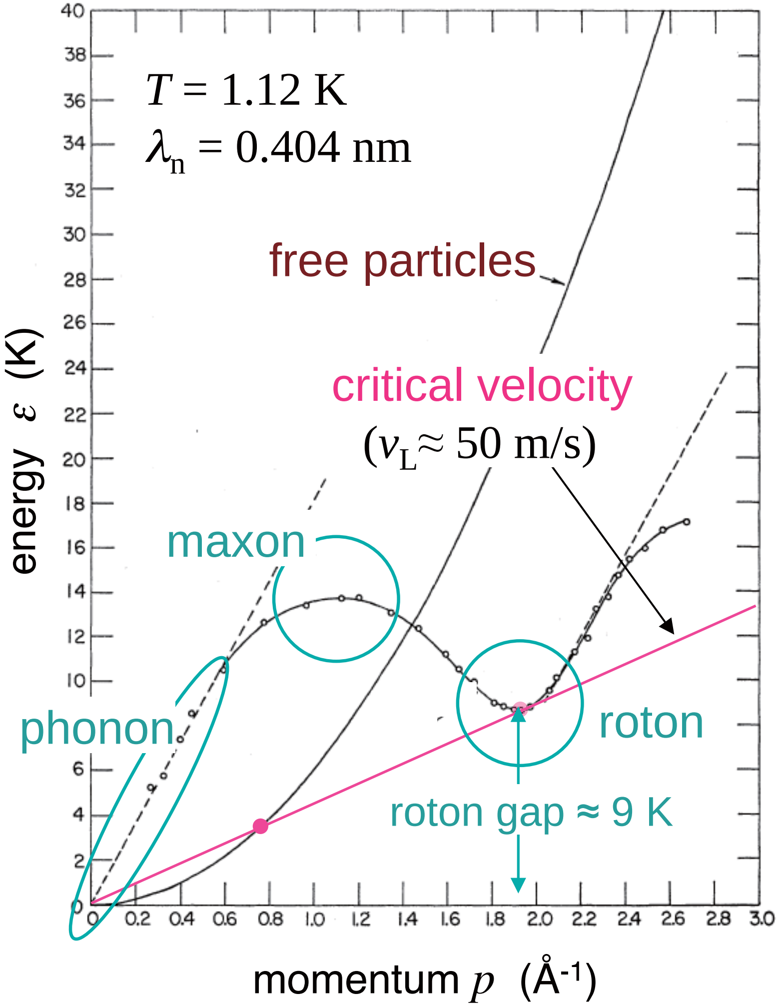
§5 Inelastic neutron scattering, specific heat and 2nd sound measurements for superfluid ^{4}He

Landau theory for elementary excitations (phonon-roton dispersion)

L.D. Landau, Phys. Rev. **60**, 356 (1941); J. Phys. USSR **5**, 71 (1941); *ivid.* **8**, 1 (1944); *ivid.* **11**, 91 (1947)

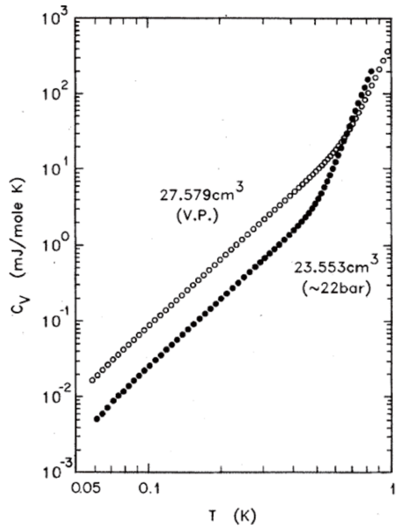
Inelastic neutron scattering

D.G. Henshaw and A.D.B. Woods, Phys. Rev. **121**, 1266 (1961)



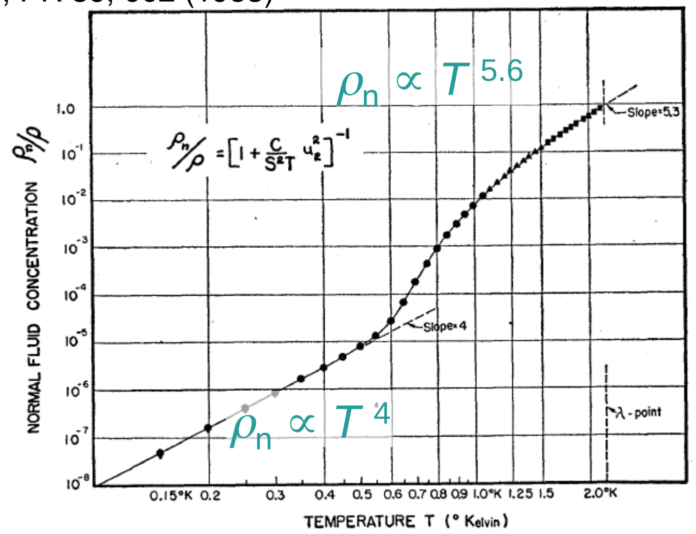
specific heat

D.S. Greywall, PRB **18**, 2127 (1978)



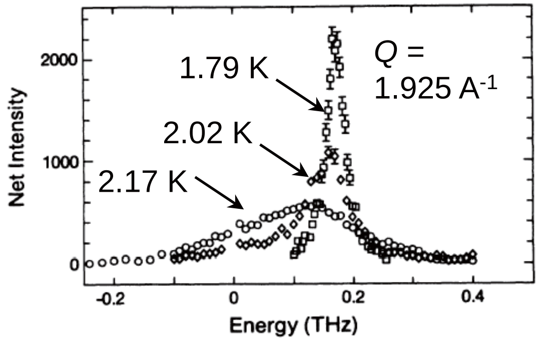
2nd sound

D. de Klerk et al., PR **89**, 662 (1953)

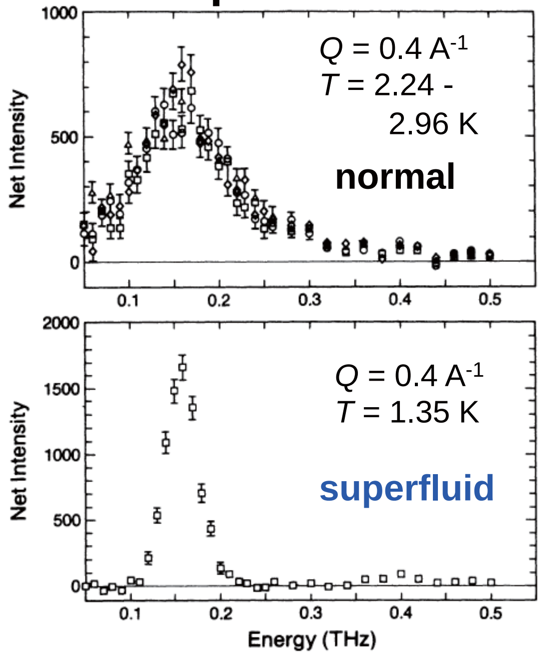


T-dependence of phonon-roton dispersion in liq. ^{4}He through T_λ

roton

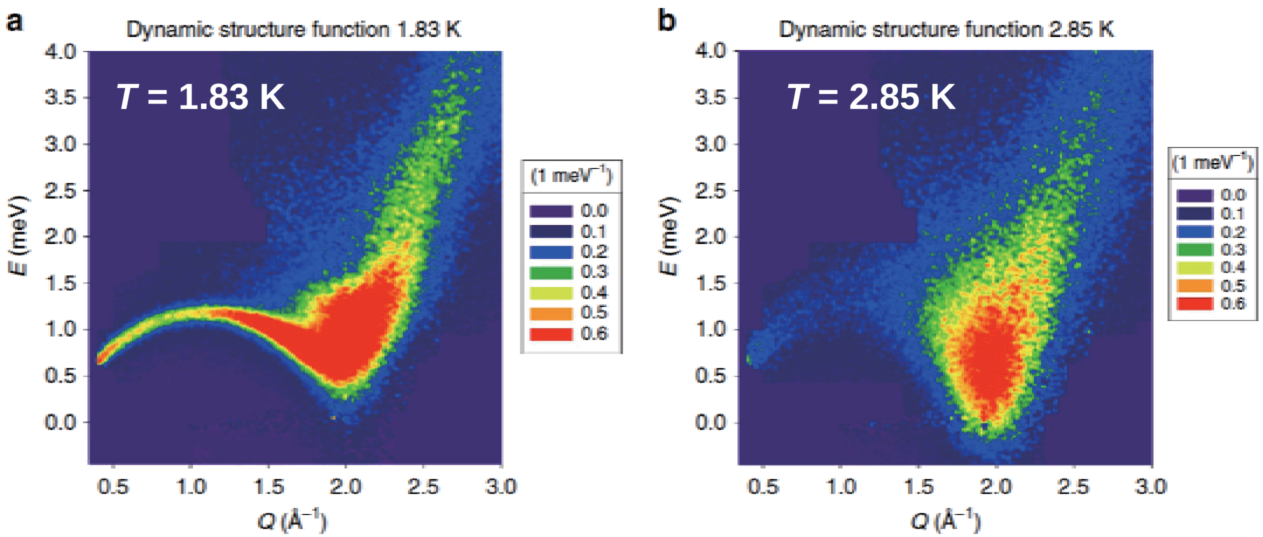


phonon

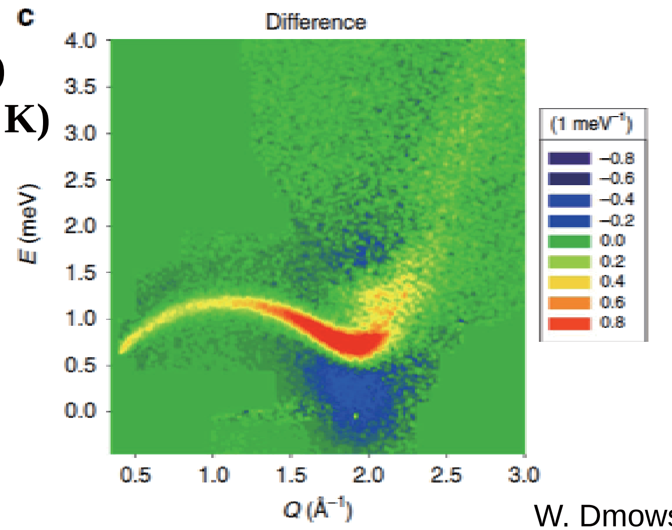


W.G. Stirling and H.R. Glyde, PRB **41**, 4224 (1990)

dynamic structure factor: $S\,(q,\,\omega)$



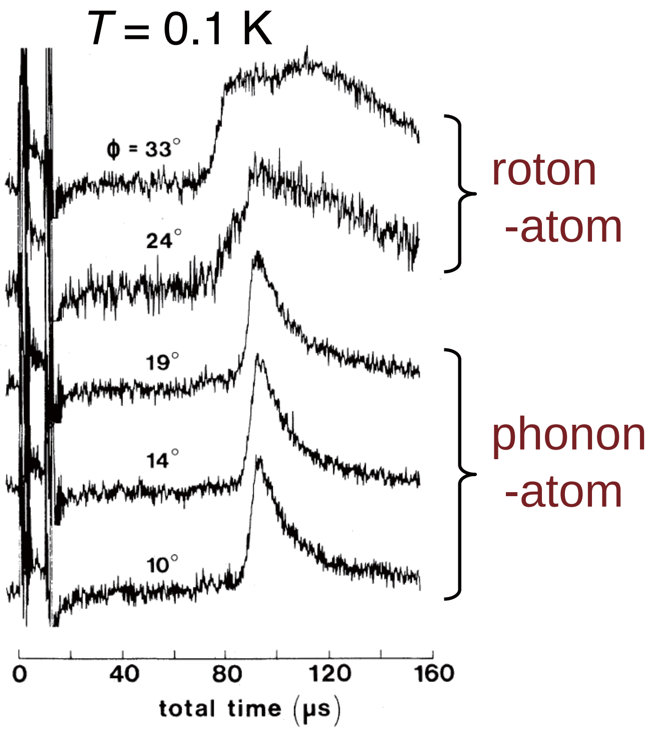
$S\,(q,\omega,\,T = 1.83\text{ K})$
$-\,S\,(q,\omega,\,T = 2.85\text{ K})$

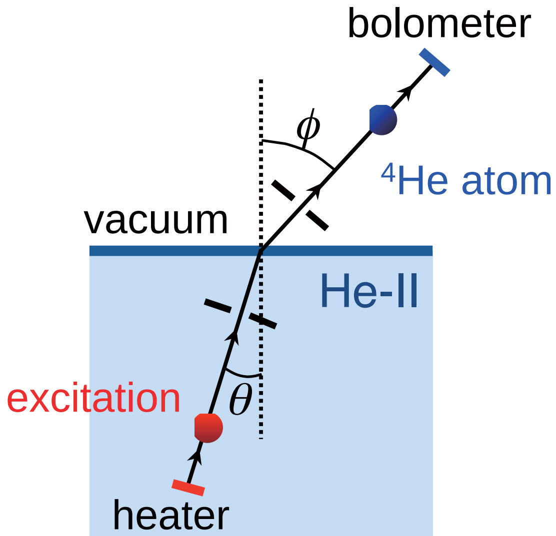


W. Dmowski et al., Nat. Commun. **8**, 15294 (2017

Quantum evaporation from He-II

F.R. Hope, M.J. Baird, A.F.G. Wyatt, PRL **52**, 1528 (1984)



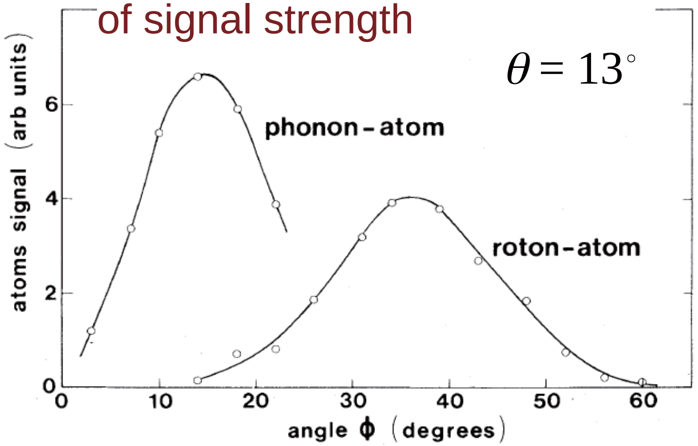


One phonon (roton) evaporates one atom.

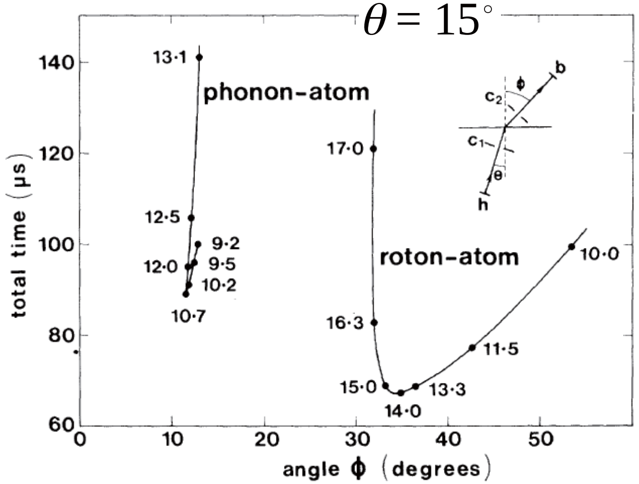
$$\begin{cases} \varepsilon = E_B + \dfrac{\hbar^2 q^2}{2m_4} \\ k\sin\theta = q\sin\phi \end{cases}$$

$$\therefore \quad \sin\phi = \frac{\hbar k \sin\theta}{\sqrt{2m_4(\varepsilon - E_B)}}$$

measured angle dependence of signal strength



calculated total travel time



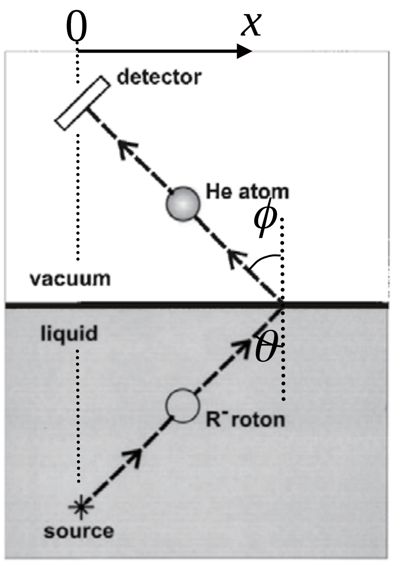
k (ε) : wave number (energy) of excitation in He-II

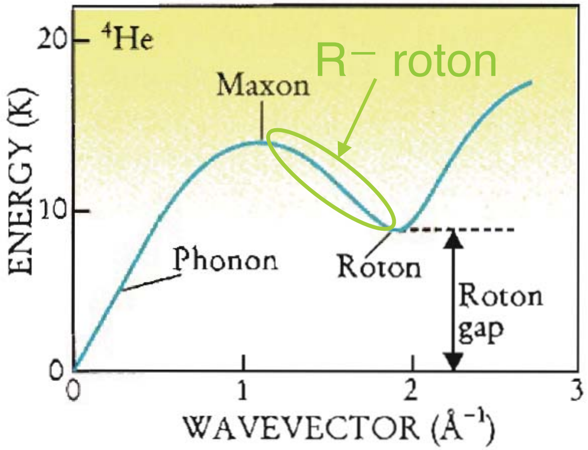
E_B: binding energy for surface ^{4}He atom

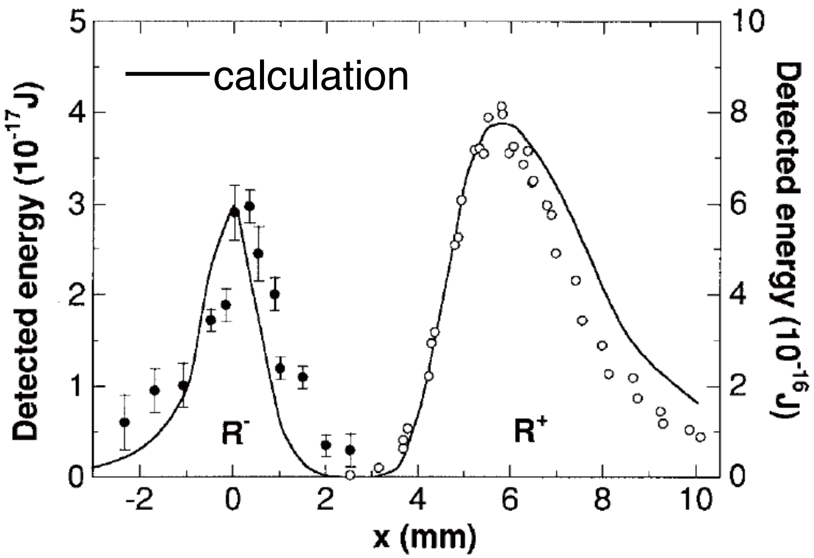
q: wave number of evaporated ^{4}He atom

Evidence for negative group velocityof R⁻ roton

M.A.H. Tucker, A.F.G. Wyatt,
Nature **283**, 1150 (1999)

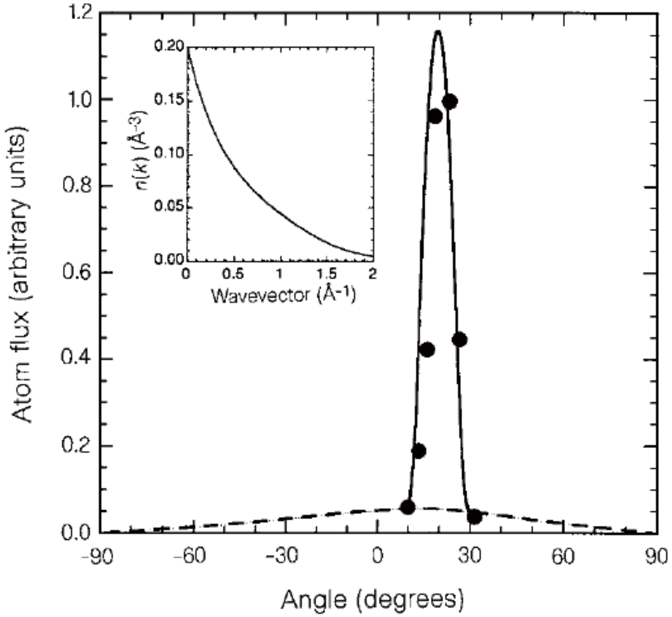






Bose Einstein condensate

A.F.G. Wyatt, Nature **391**, 56 (1998)

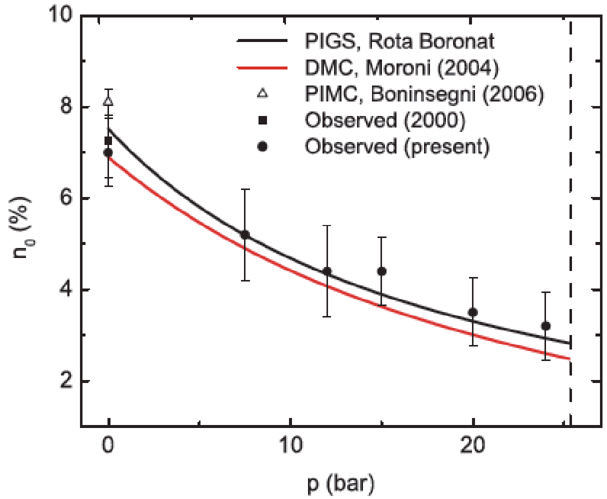


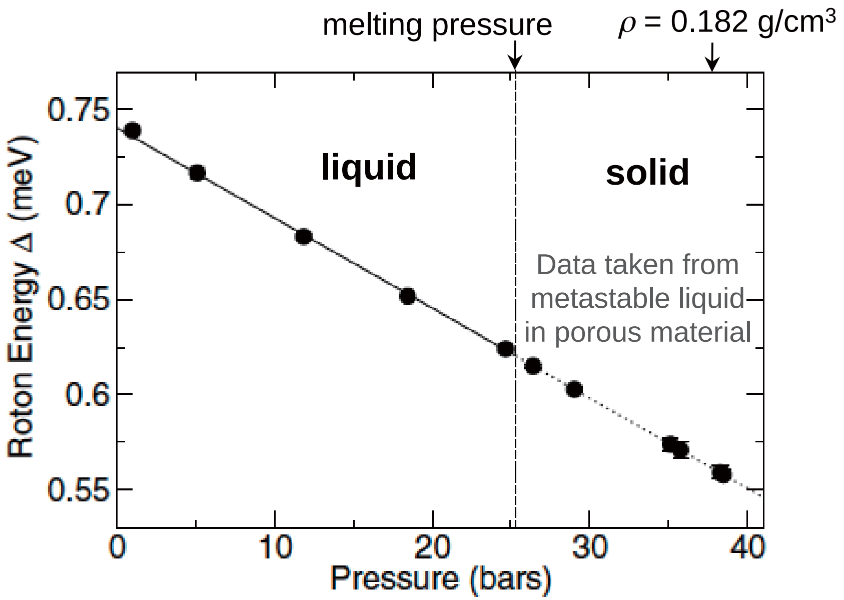
Pressure (density) dependencies of Δ_r and n_0 determined from neutron experiments

- Roton gap (Δ_r) in metastable liquid ^{4}He seems to vanish at a very high pressure, $P \approx 160$ bars ($\rho \approx 0.22$ g/cm^3).
  P-*ρ* relation: L. Vrangeš et al., PRL **95**, 145302 (2005)

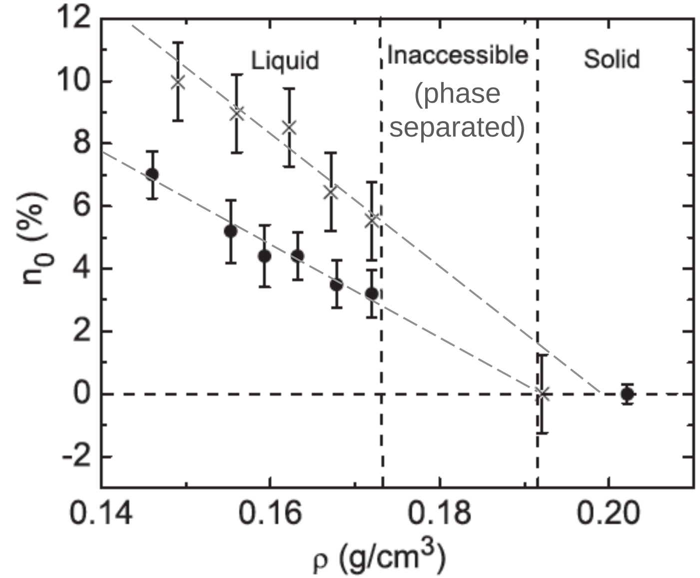
- Condensation fraction (n_0) seems to vanish at a relatively low density, $\rho = 0.19-0.20$ g/cm^3, which is close to the lowest density of hcp ^{4}He.

  → Metastable superfluid ^{4}He with $n_0 = 0$ can exist in a wide pressure (density) range.





J.V. Pearce et al., PRL **93**, 145303 (2004)



H. R. Glyde et al., PRB **83**, 100507(R) (2011)

Isotope effect on quantum melting

1. the zero-point motion favors delocalization as well known. But, this is true only when $a \gg \sigma$ (low ρ)
   a : interparticle distance σ : hardcore diameter

2. When $a \approx \sigma$, the zero-point motion favors localization

Solid phase has more isotropic **shape** of Ω than liquid phase Y. Nagaoka, Prog. Theor. Phys. Suppl. **69**, 335 (1980)

Ω : 3*N*-dimensional configuration space in which *N* particles move around

cf. $\Omega_{\text{solid}} \approx \Omega_{\text{liquid}}$

Solid phase has lower kinetic energy (K) by 2−4 K than liquid phase at the same densities.

$$K \approx \frac{\hbar^2}{mL^2}$$

L: shortest linear dimension of Ω

Quantum solids should always have *negative* isotope effect on T_{melt}.

$$\frac{dT_{\text{melt}}}{dm} < 0$$

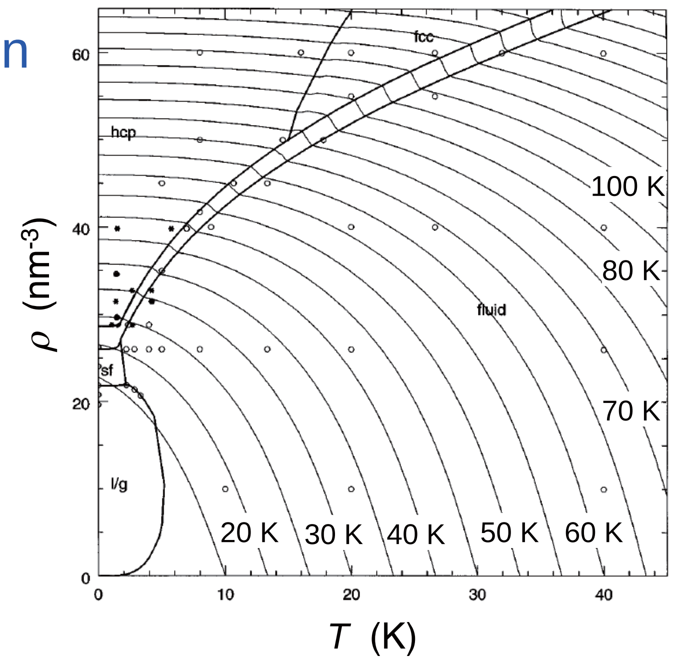
3. The same is true in 2D solid in a periodic potential.

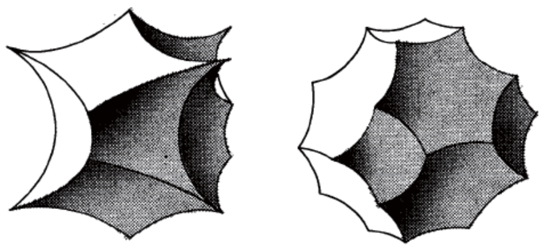
e.g., commensurate phase

D. S. Hirashima, T. Momoi, and T. Takagi, J. Phys. Soc. Jpn. **72**, 1446 (2003).

PIMC calculation of K in liquid and solid ^{4}He

D.M. Ceperley et al., PRL **77**, 115 (1996)





Ω in hcp phase Ω in bcc phase