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educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

SMR.1348 - 5

**SECOND EUROPEAN SUMMER SCHOOL on
MICROSCOPIC QUANTUM MANY-BODY THEORIES
and their APPLICATIONS**

(3 - 14 September 2001)

QUANTUM EVAPORATION, CONDENSATION AND ATOM REFLECTION

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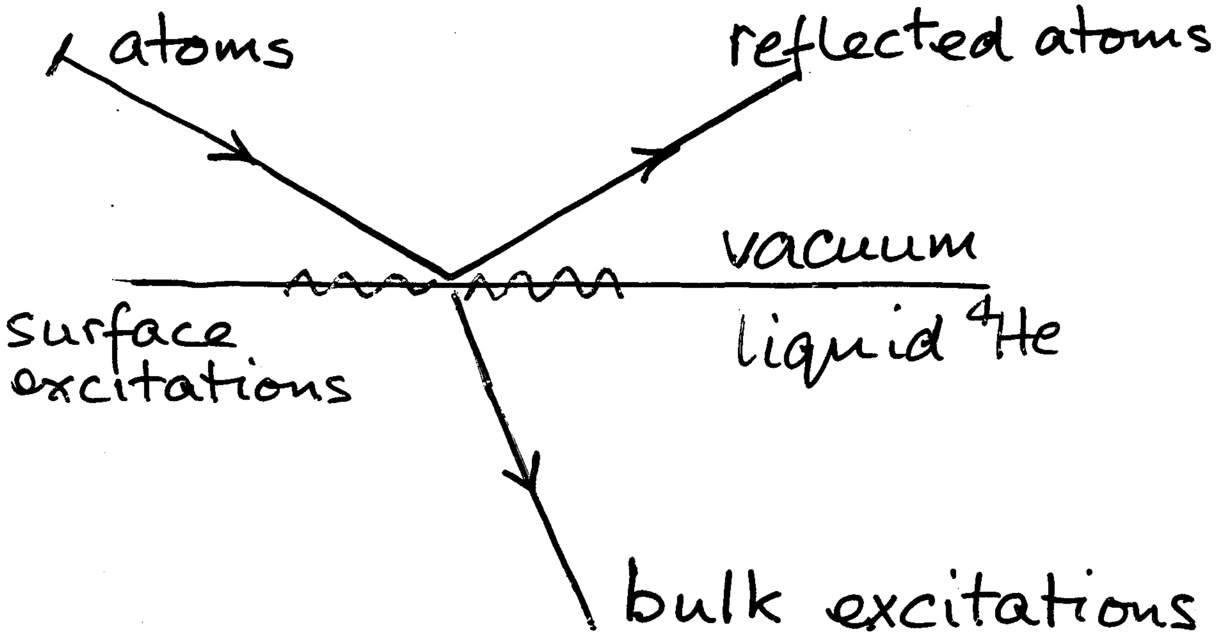
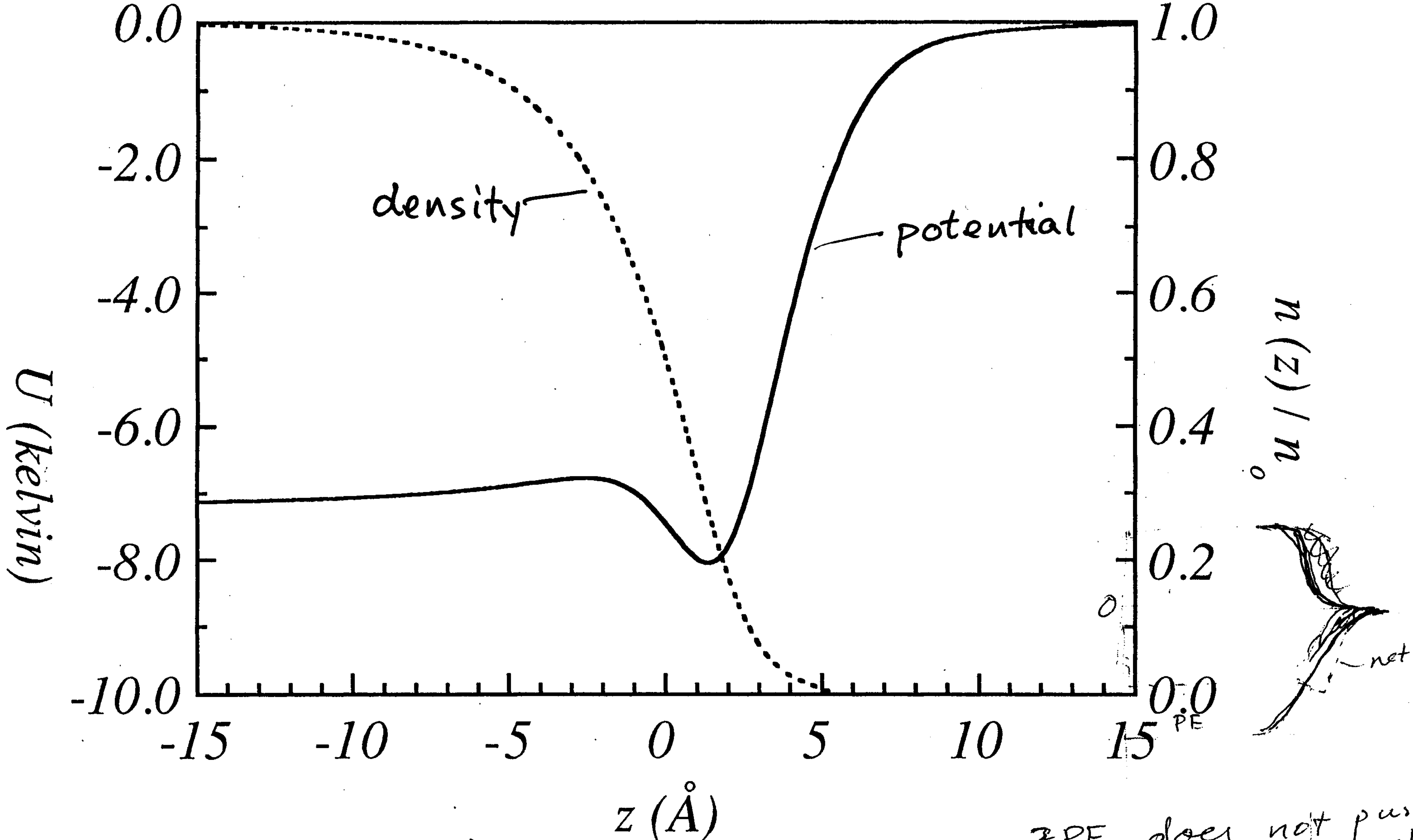
Exeter EX4 4QL
U.K.**

These are preliminary lecture notes, intended only for distribution to participants

Atom beams incident on liquid ^4He

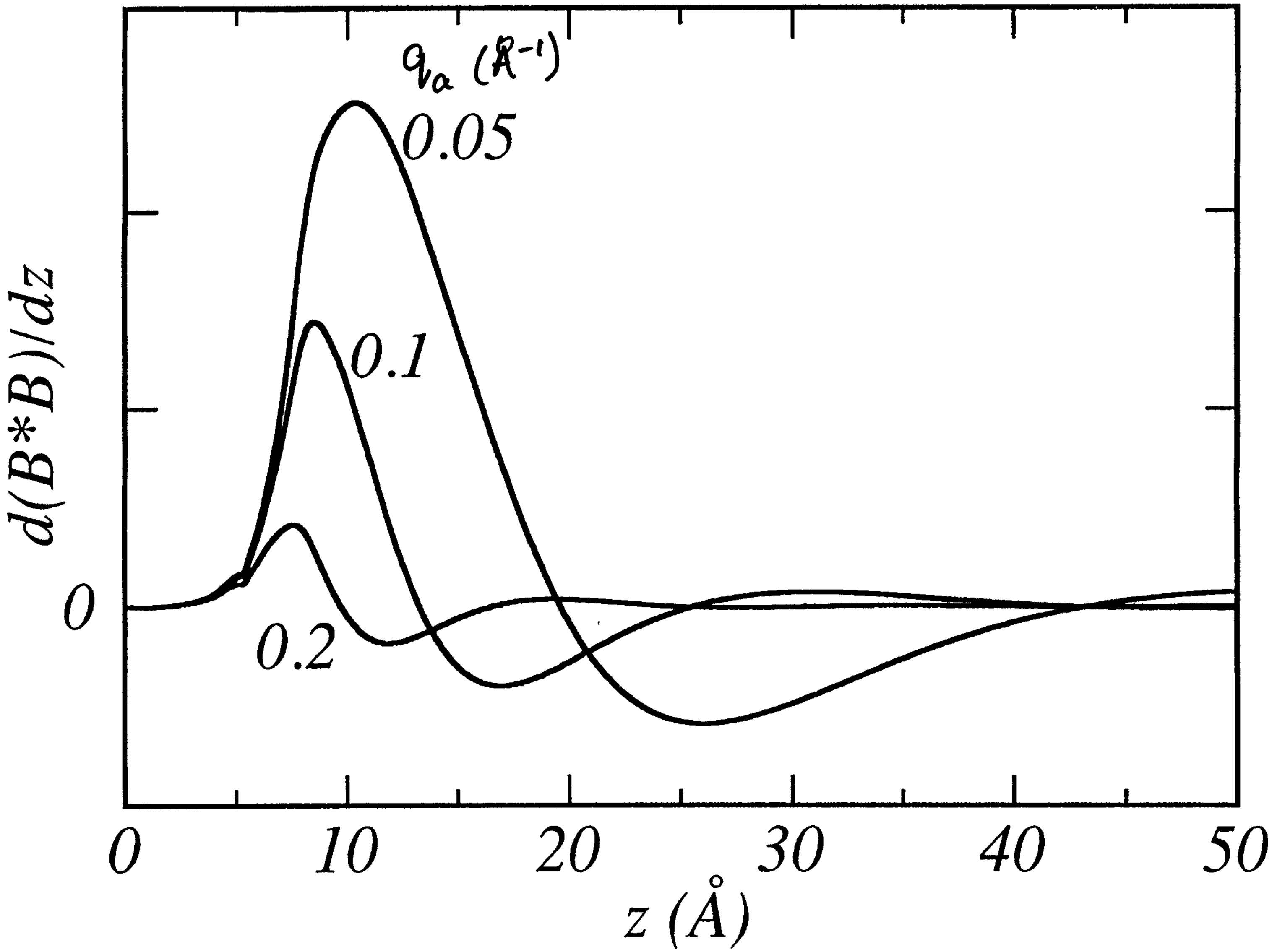




in liquid ^{4}He, Potential energy ≈ −20
zero point energy 13
−7 K

ZPE does not push up energy so much at 1½ Å i.e. ZPE change faster than the PE

②



B*B is reflected intensity.

(3)

Edwards et al

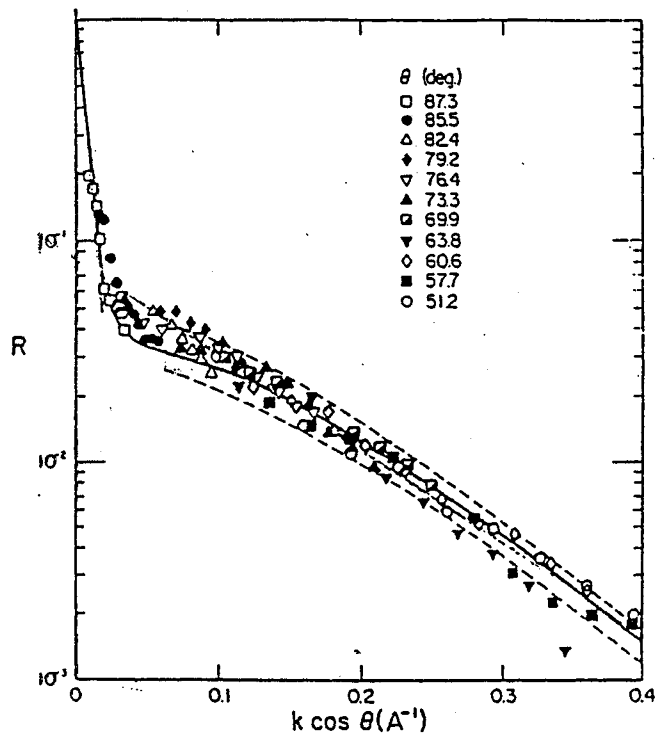
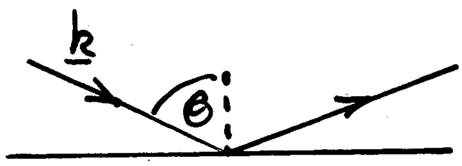
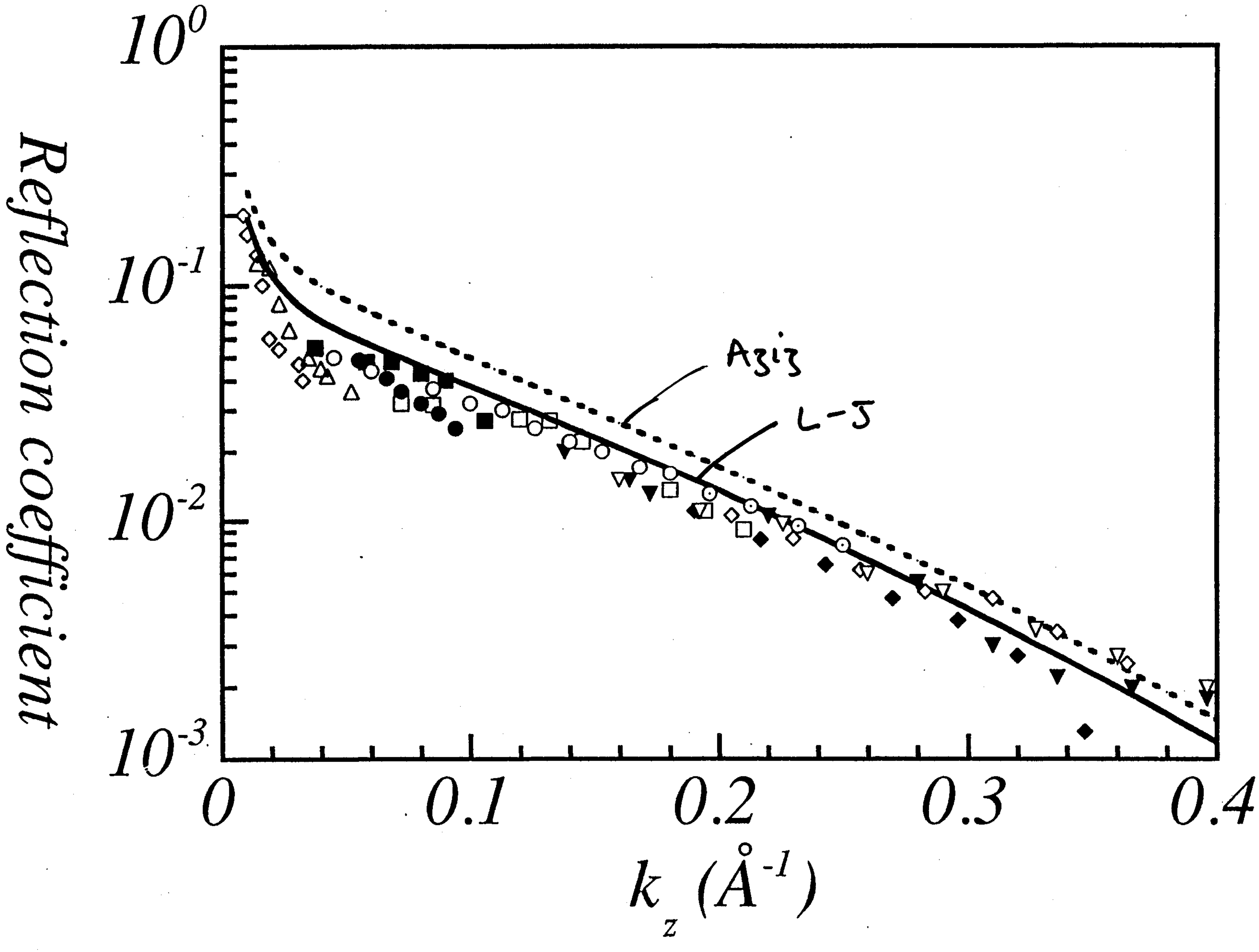


FIG. 2. Measurements of the reflectivity R as a function of k_z, the perpendicular wave vector of the atom. The data are compared with the EF theory (curve) and with the measurements of Ref. 1 which, if plotted, would lie between the dashed lines.

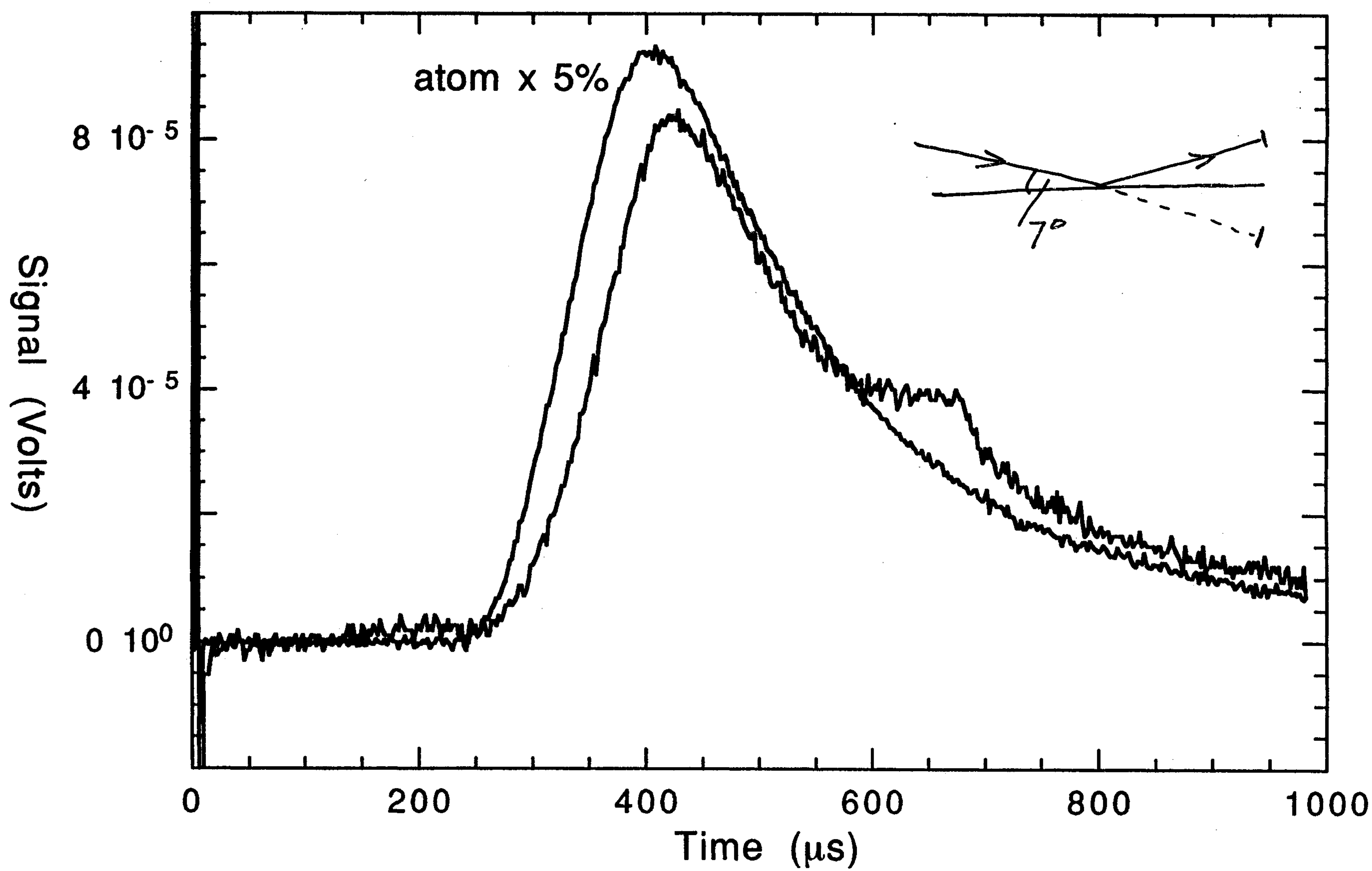


1, specular reflection
2, low reflectivity
3, reflectivity depends on momentum perpendicular to the surface
4, lower $k_\perp$ → higher reflectivity i.e. for long wavelengths the step appear more abrupt.

model fits (no tail on density profile)

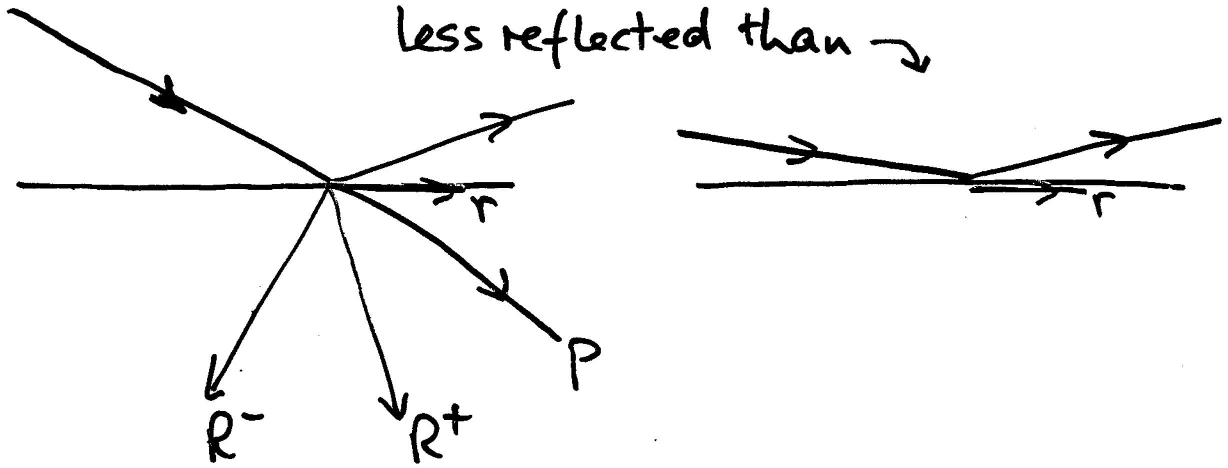


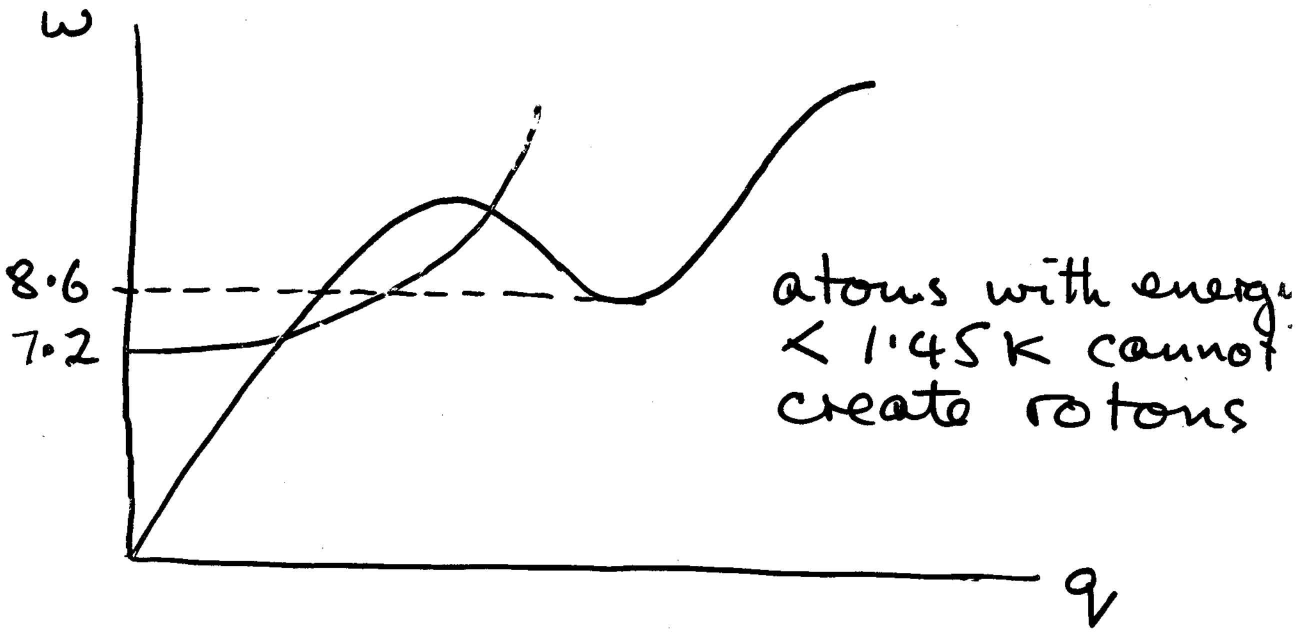
measurements from Wyatt, Tucker & Cregan



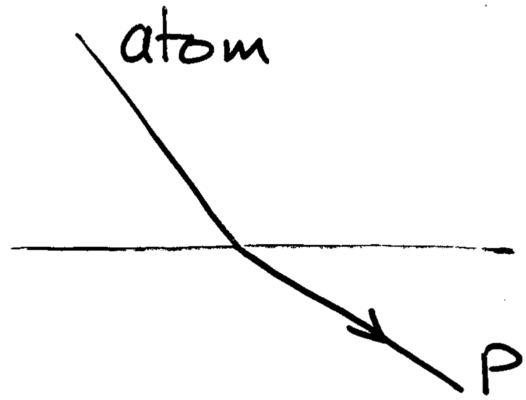
⑥

Reflection modified if creating excitations is forbidden



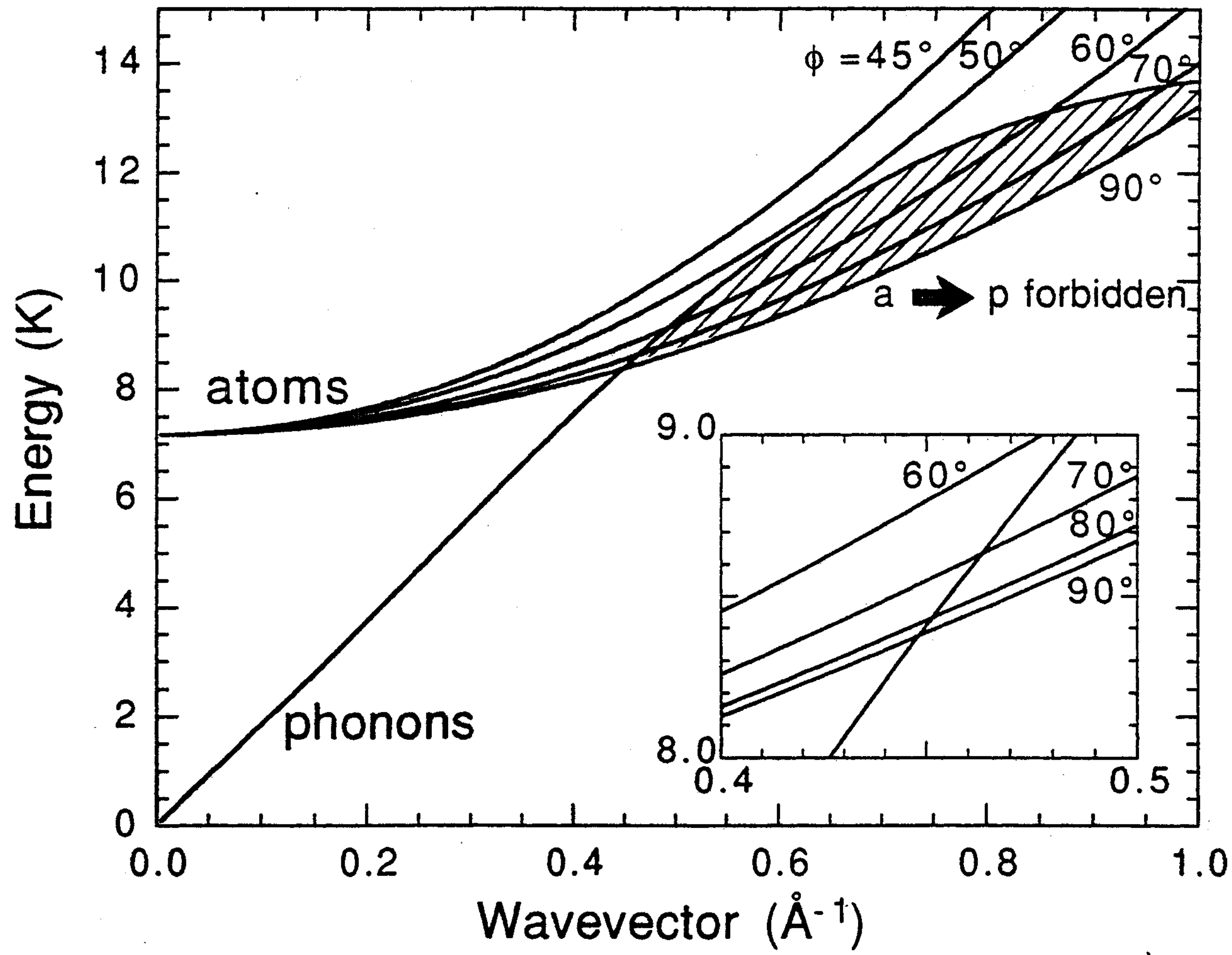


atoms with energy > 1·2 K have more momentum than the excitation



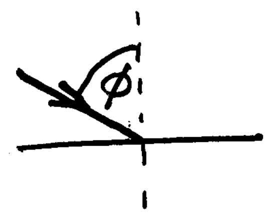
conservation of parallel momentum forbids a phonon being created.

For 83° angle of incidence, atoms with energy > 1·24 K cannot create one or more phonons ⑧



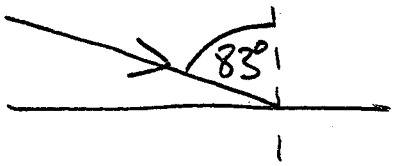
$k_{atom} \sin\phi$

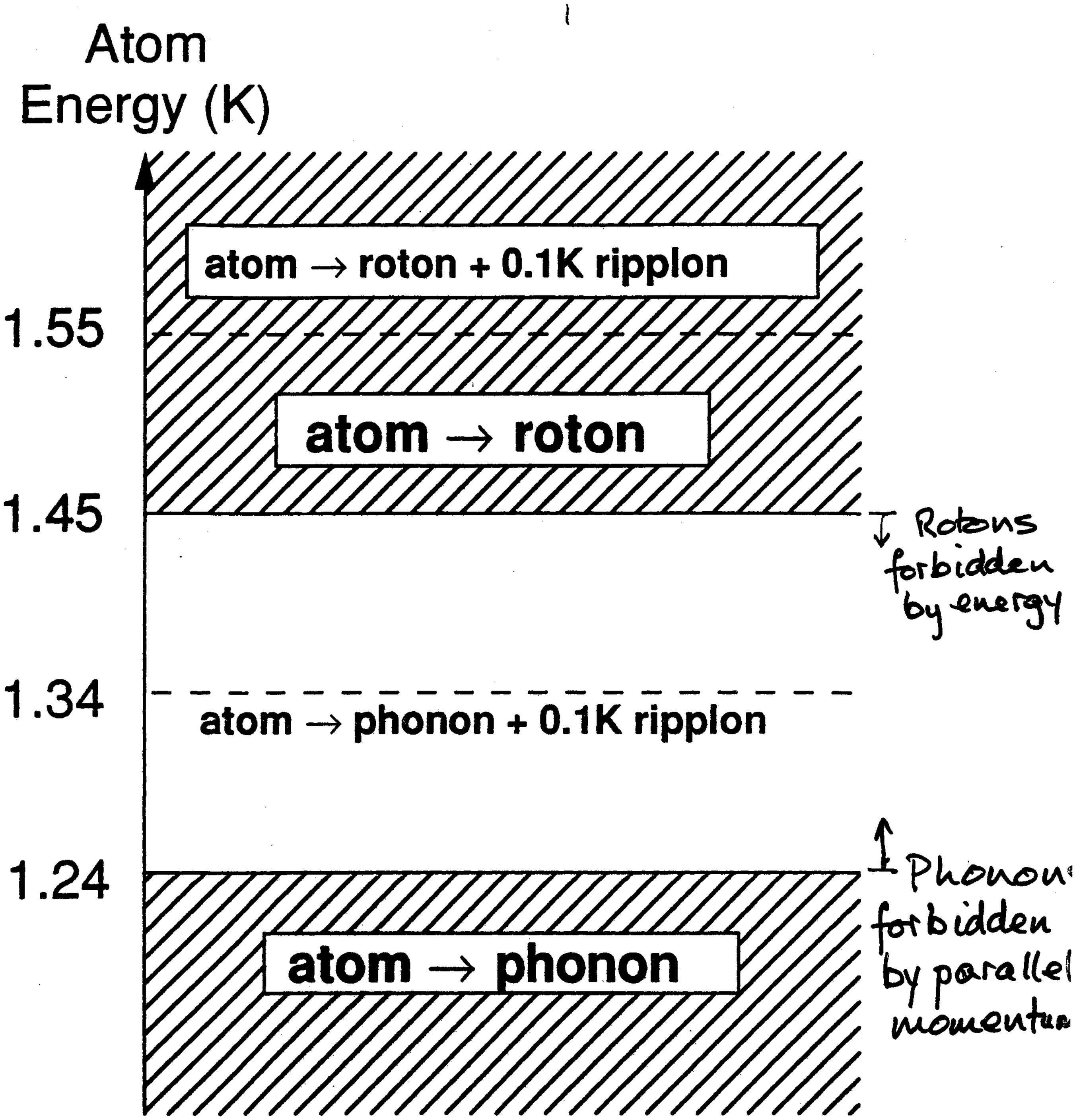
q_{phonon}

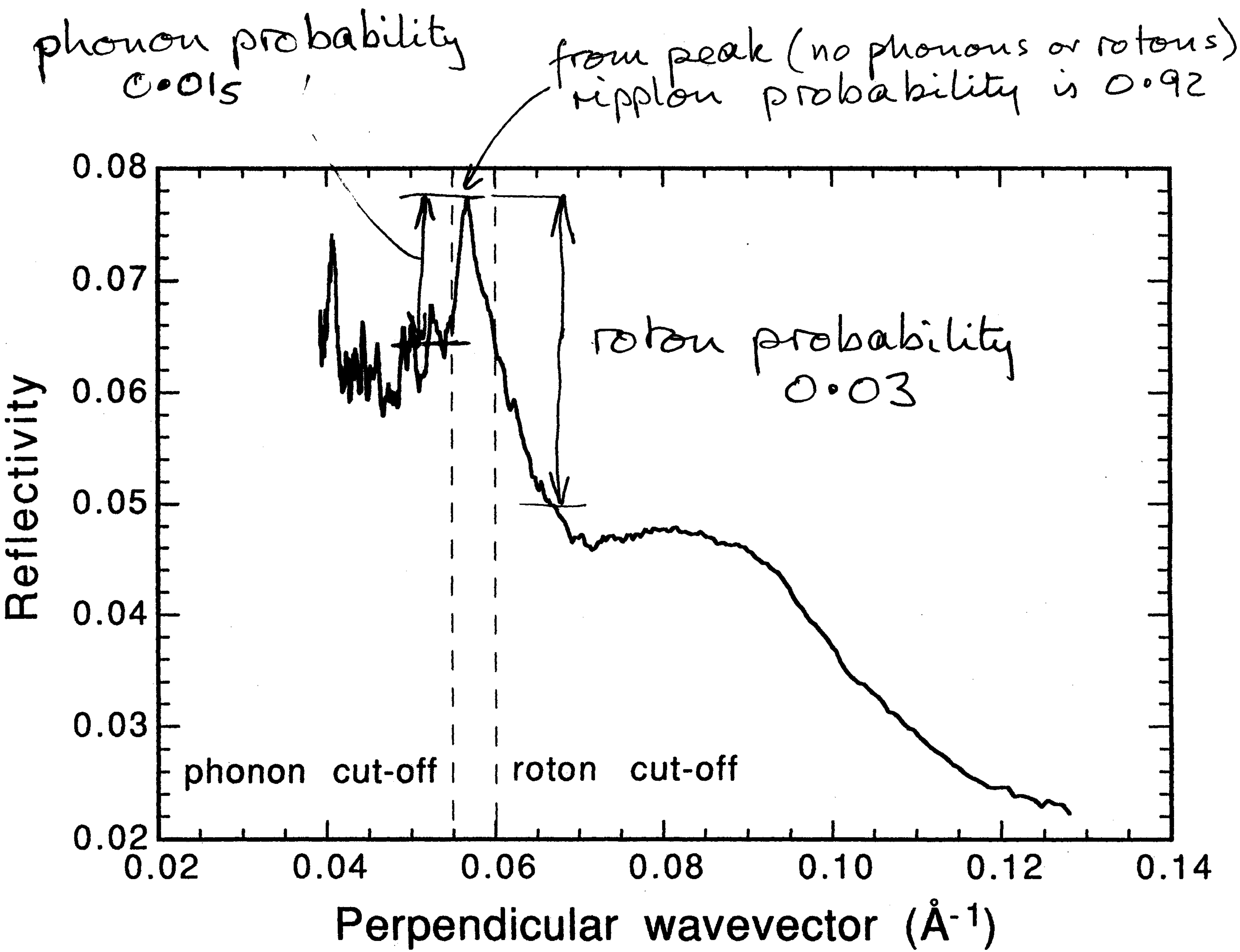


$\{ k_a \sin\phi$, q_{ph}

and q_{ph}


83°


Atom
Energy (K)
atom → roton + 0.1K ripplon
1.55
atom → roton
1.45
Rotons forbidden by energy
1.34
atom → phonon + 0.1K ripplon
1.24
Phonons forbidden by parallel momentum
atom → phonon



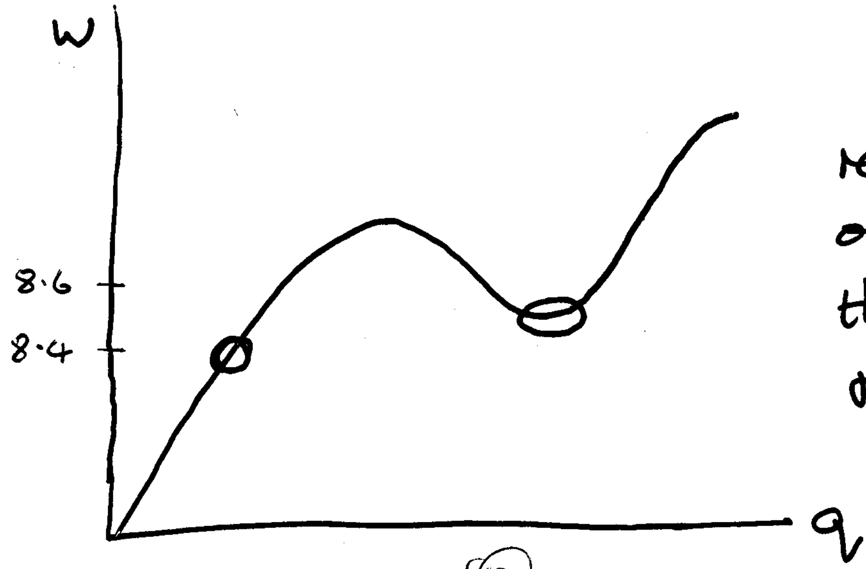
phonon probability
0·015
from peak (no phonons or rotons)
ripplon probability is 0·92
roton probability
0·03
Reflectivity
0.08
0.07
0.06
0.05
0.04
0.03
0.02
phonon cut-off
roton cut-off
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Perpendicular wavevector (Å-1)

(1)

probabilities

phonons	1·5%	at least
rotons	3·0%	— " —
ripplons	92%	at most

away from this energy window all we see is a low atom reflectivity — we do not know if there are more rotons and less ripplons produced.



reflection meas^nts only relate to these phonons & rotons

Conclusions

Evaporation

- one to one process, P, R^- & $R^+ \rightarrow$ atom
- energy is conserved
- momentum parallel to surface is conserved
- R^+ rotons created by the heater
- high energy phonons created in the liquid
- R^- rotons created from R^+ rotons
- quantum efficiency:

$P \rightarrow a$ 0·1
$R^+ \rightarrow a$ 0·3
$R^- \rightarrow a$ 10^{-3}
} best estimates

- perpendicular momentum is evidence for the condensate.

Reflection

- reflectivity is low, most atoms condense
- reflectivity decreases with $k_\perp$
- can see when the phonon & roton creation channels are blocked

Condensation

- Ripplons are mostly produced
- one to one processess

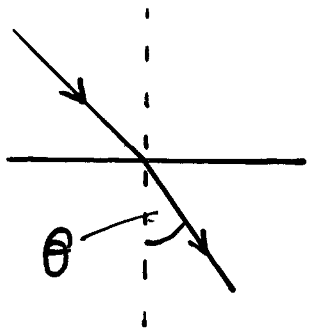
$a \rightarrow P$ very weak
$a \rightarrow R^+$ moderate
$a \rightarrow R^-$ zero

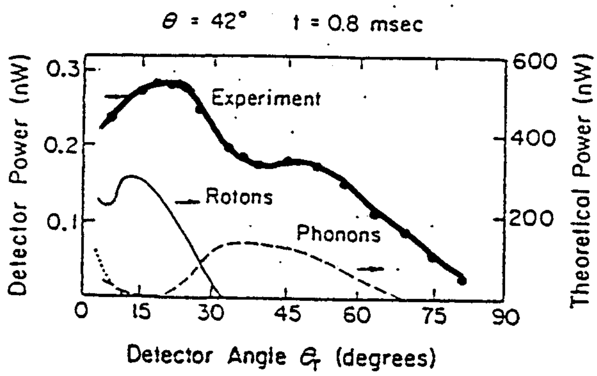
- one to two process

$a \rightarrow 2P$ weak

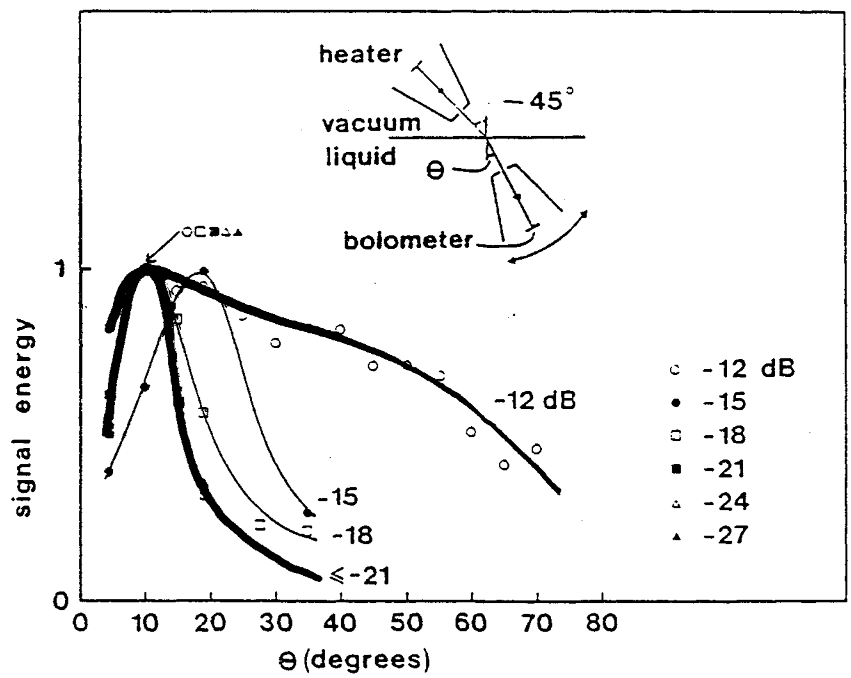
Condensation

Edwards et al

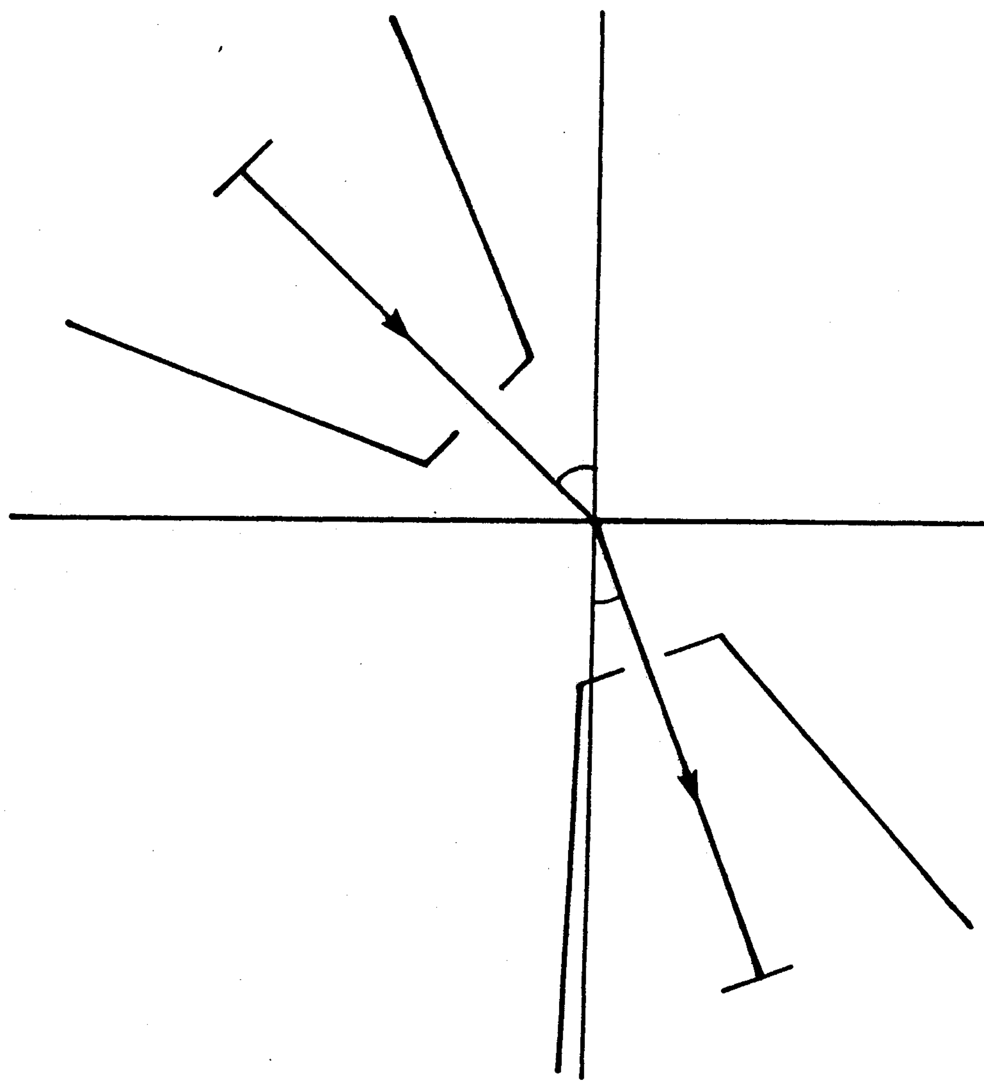




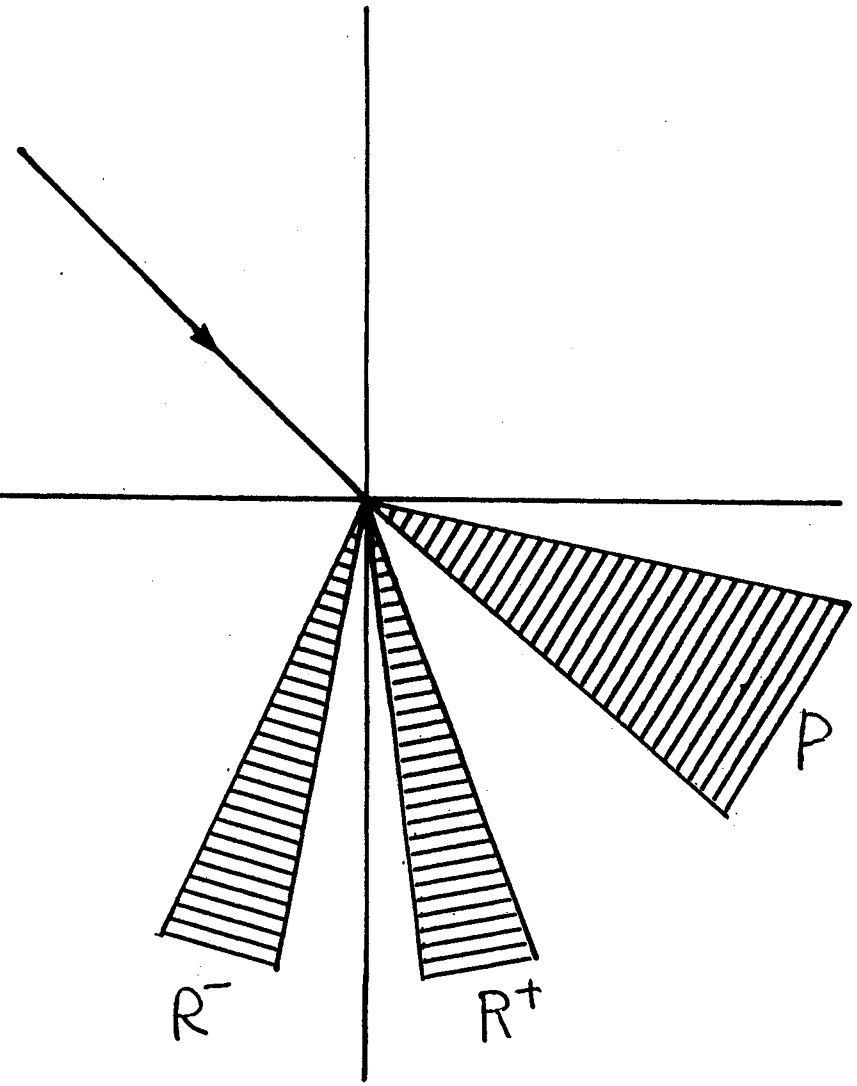
Brown & Wyatt

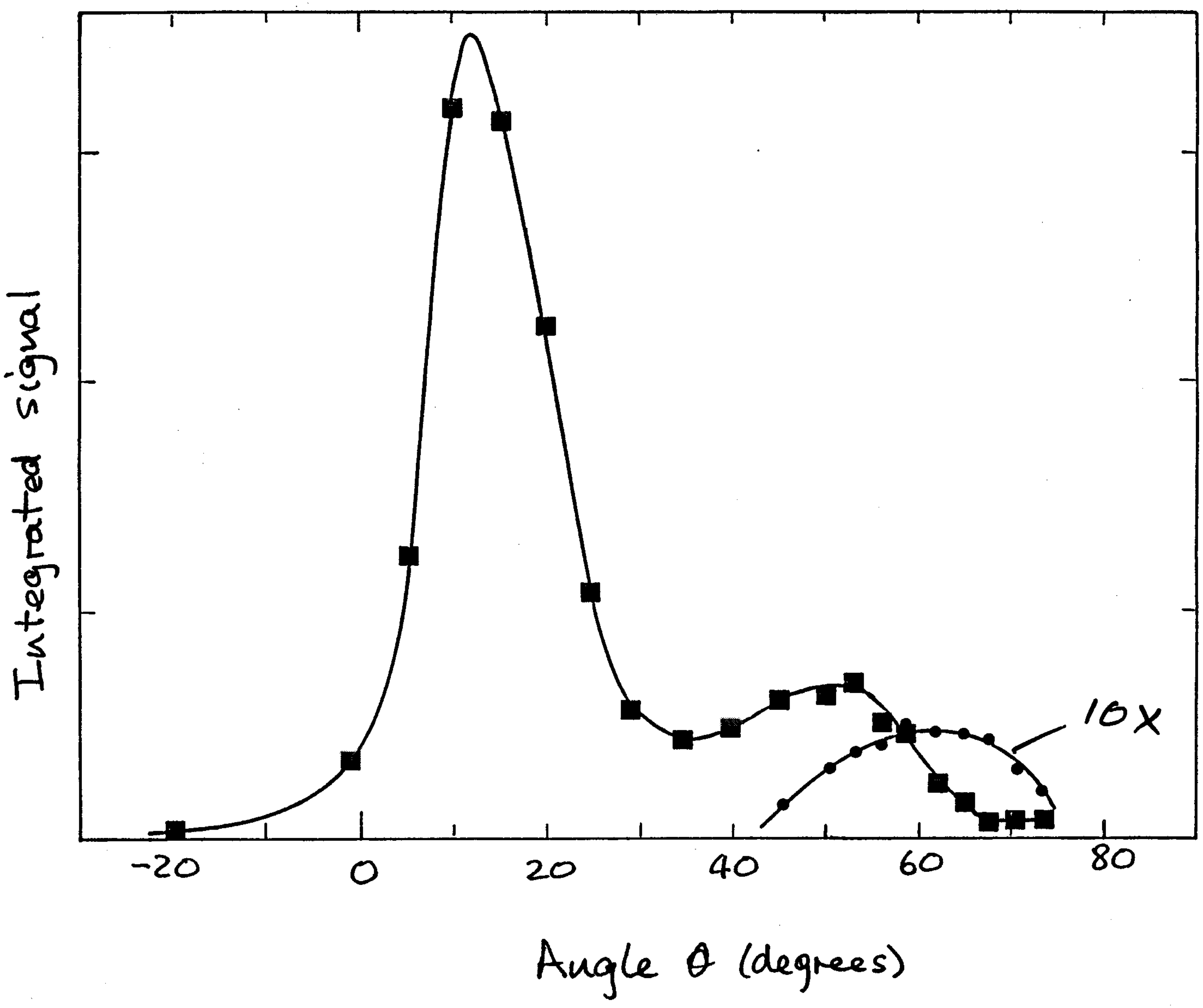


Surface is being spoiled by the high flux of atoms apparatus



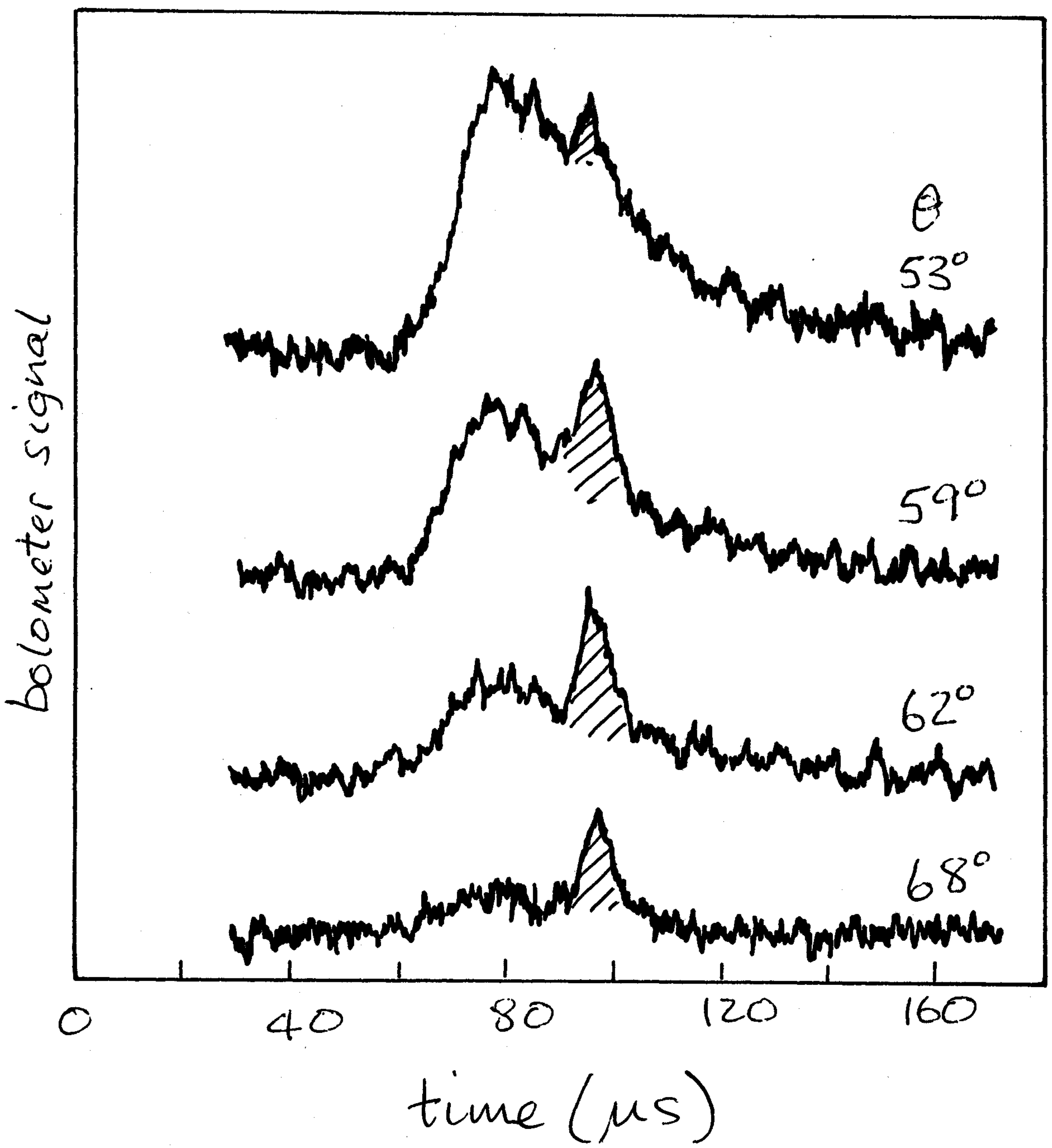
might expect.

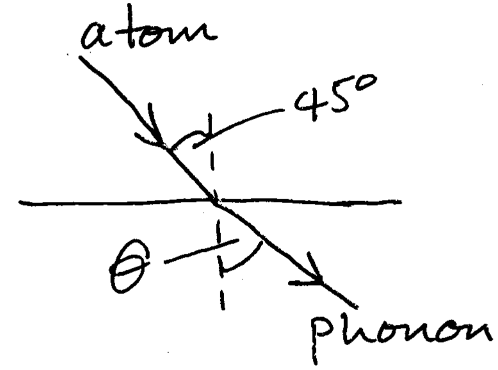




Integrated signal
-20
0
20
40
60
80
10X
Angle θ (degrees)

at "phonon" angle

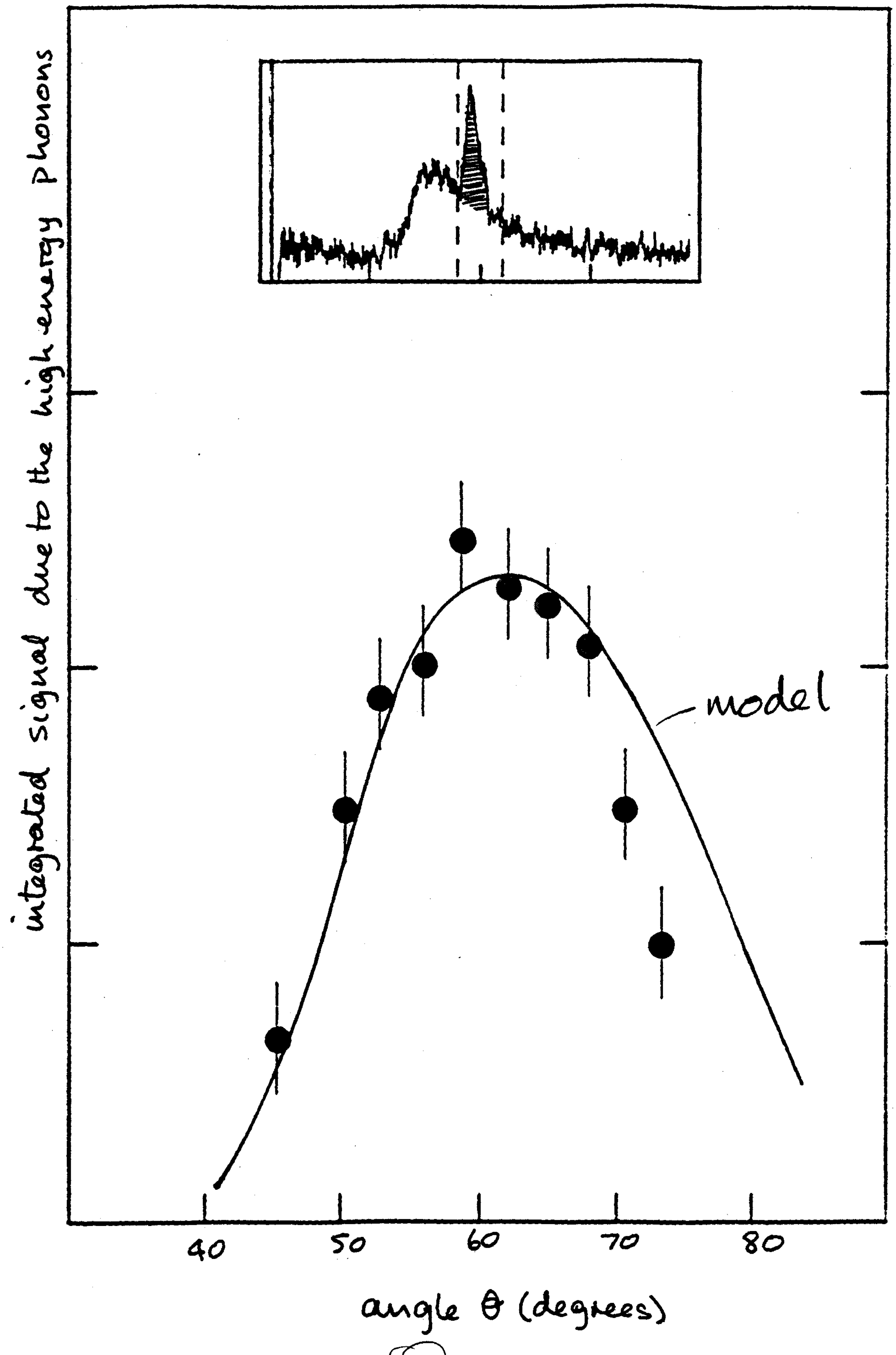




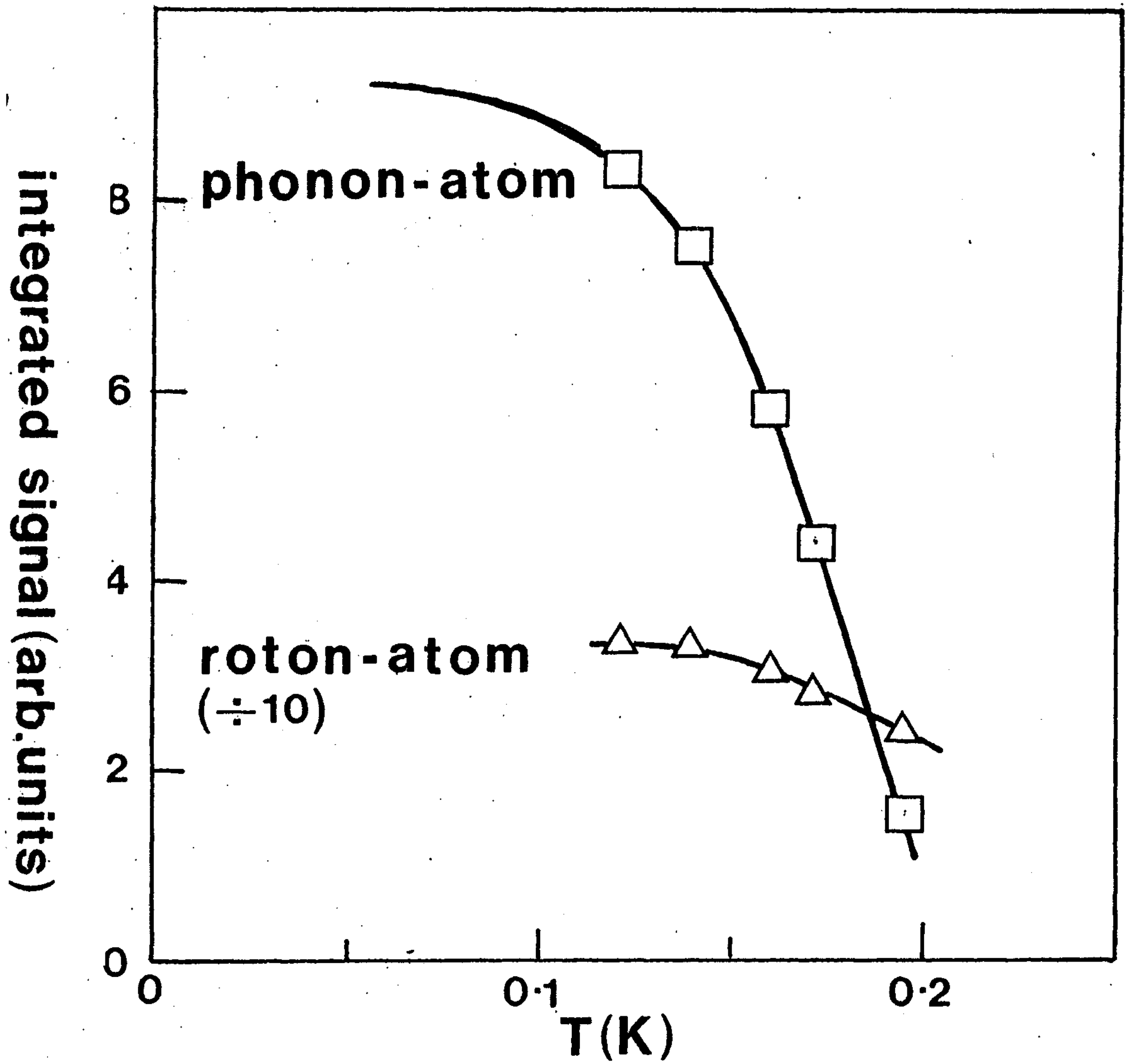
1 atom → 1 phonon signal

NB this is a very weak signal

1 atom → 1 phonon

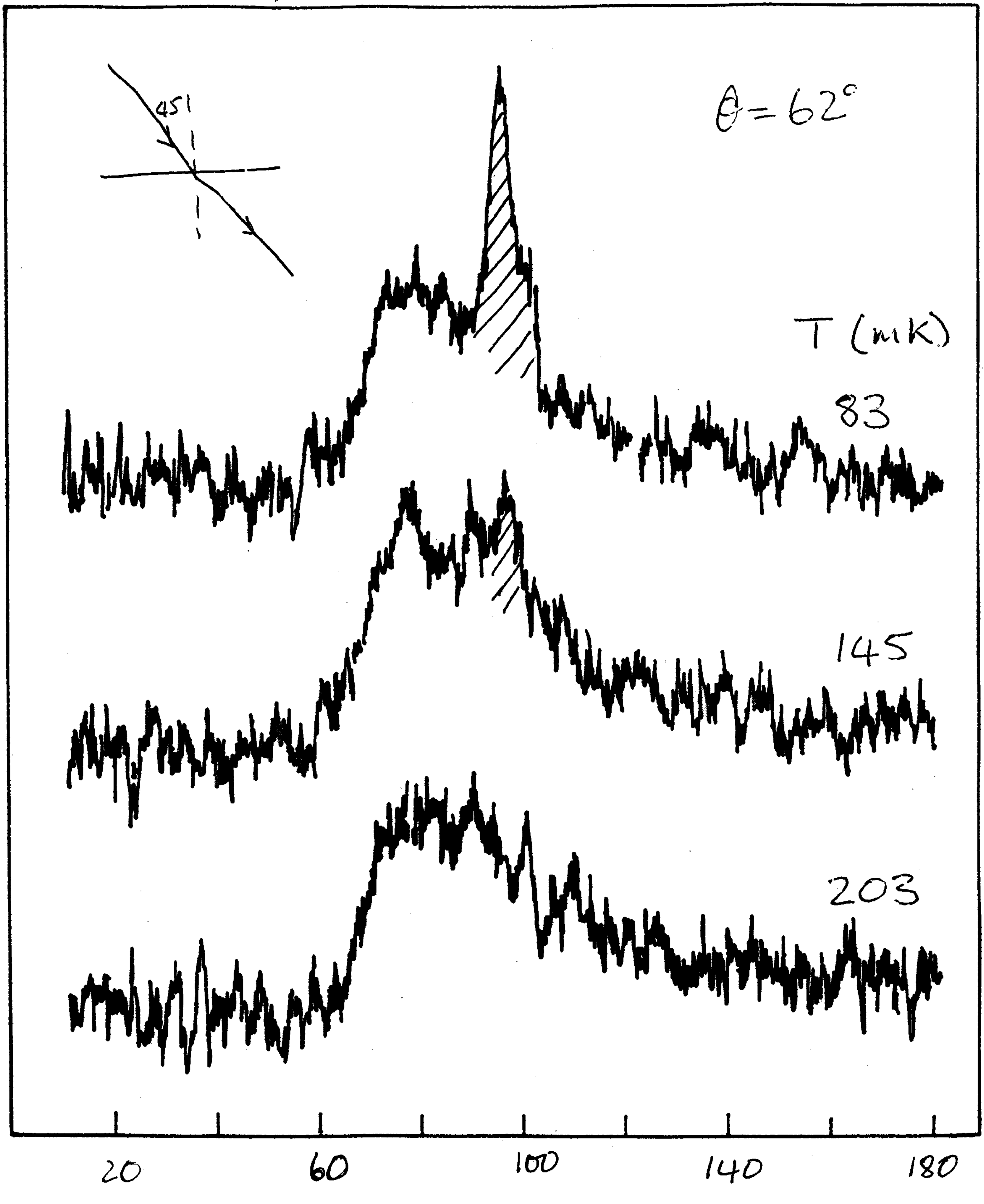


3b



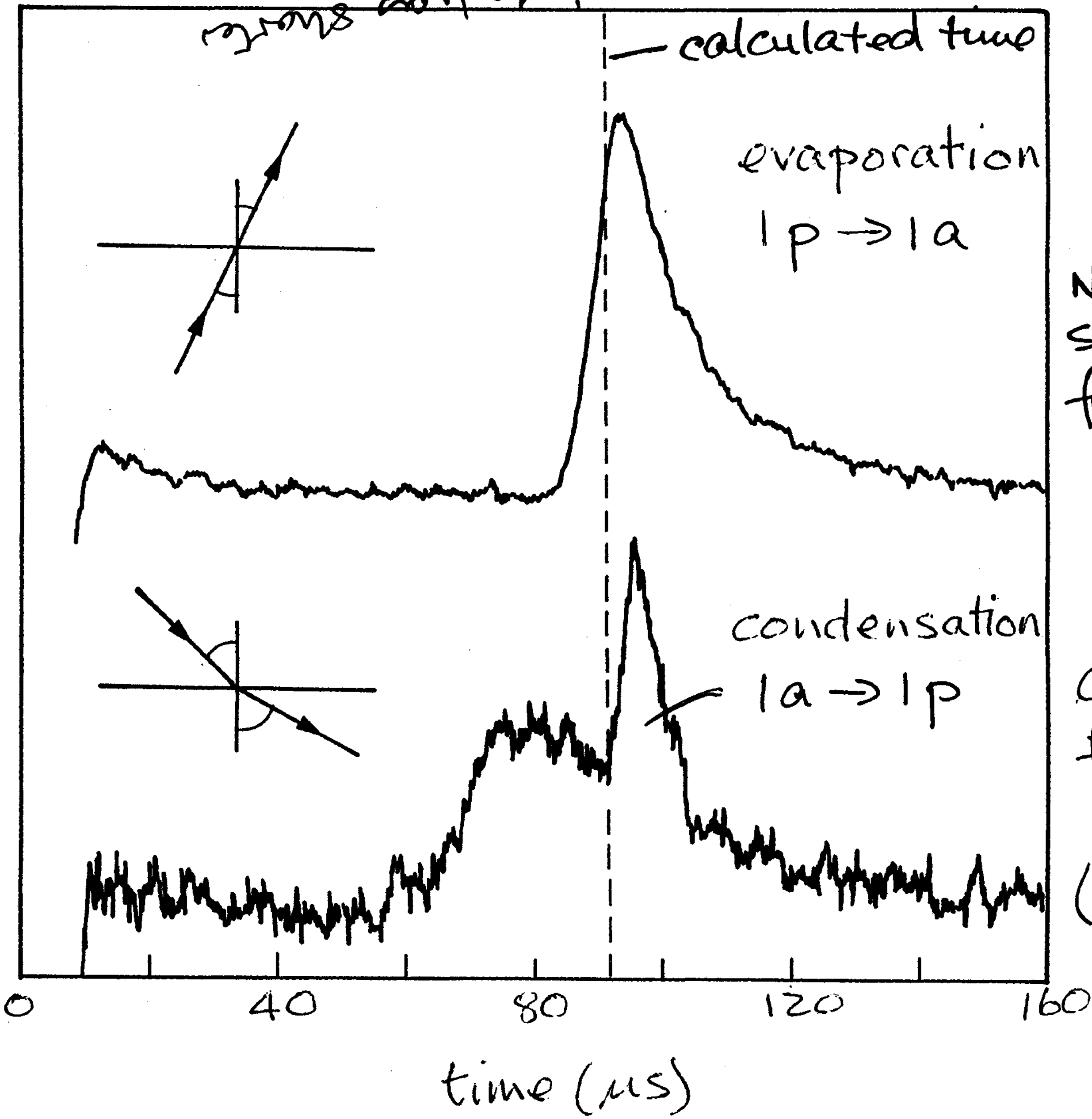
phonon-atom
roton-atom
(÷10)
integrated signal (arb.units)
0
2
4
6
8
0
0·1
0·2
T(K)

"phonon aug6"



signal decreases with He temperature in the same way as ω > 10K phonon i.e. via ~~APP~~

(20)

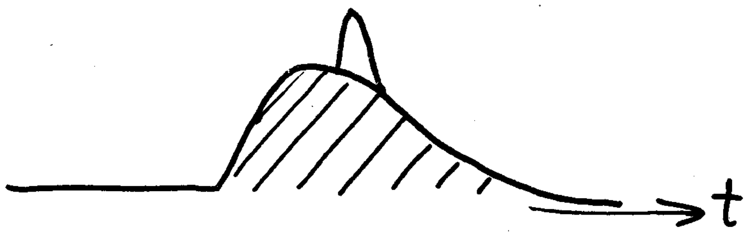


both too short
τ_c in the theory.

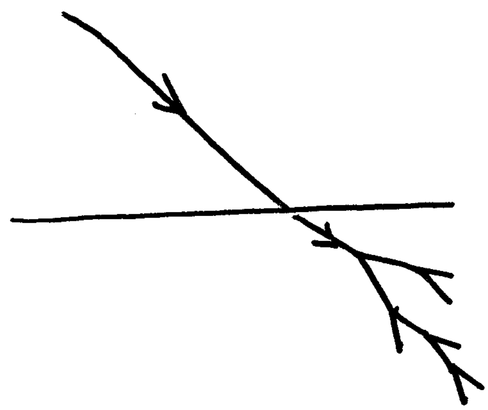
NB evaporation signal is "too fast"

correct time for 1a → 1p process (phonon ω > 10K)

The broad signal at the "phonon angle"



it is not :-



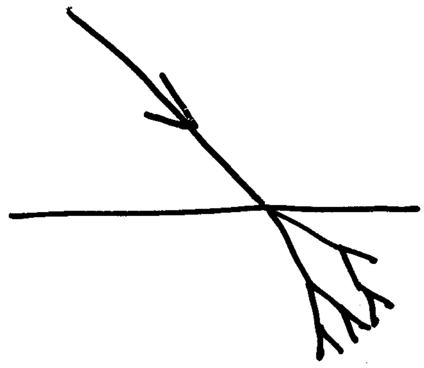
i.e. 1 atom → 1 phonon → 3pp decays
because
atom energy is less than that to produce a phonon with ω > 10 K

fastest atom is one which would create a ω = 10 K phonon

phonons will propagate at the ultrasonic velocity

fastest time for this process is 88 μs
& broad signal starts < 70 μs
to get fast signal need high energy atom

process is



i.e. 1 atom creates 2 or more phonons

some atoms have enough energy to create 1 phonon with $\omega > 10K$ (we know this from the speed of the signal)

i.e. creation of 2 or more phonons competes with the 1 phonon process. (the 1 phonon process is relatively weak

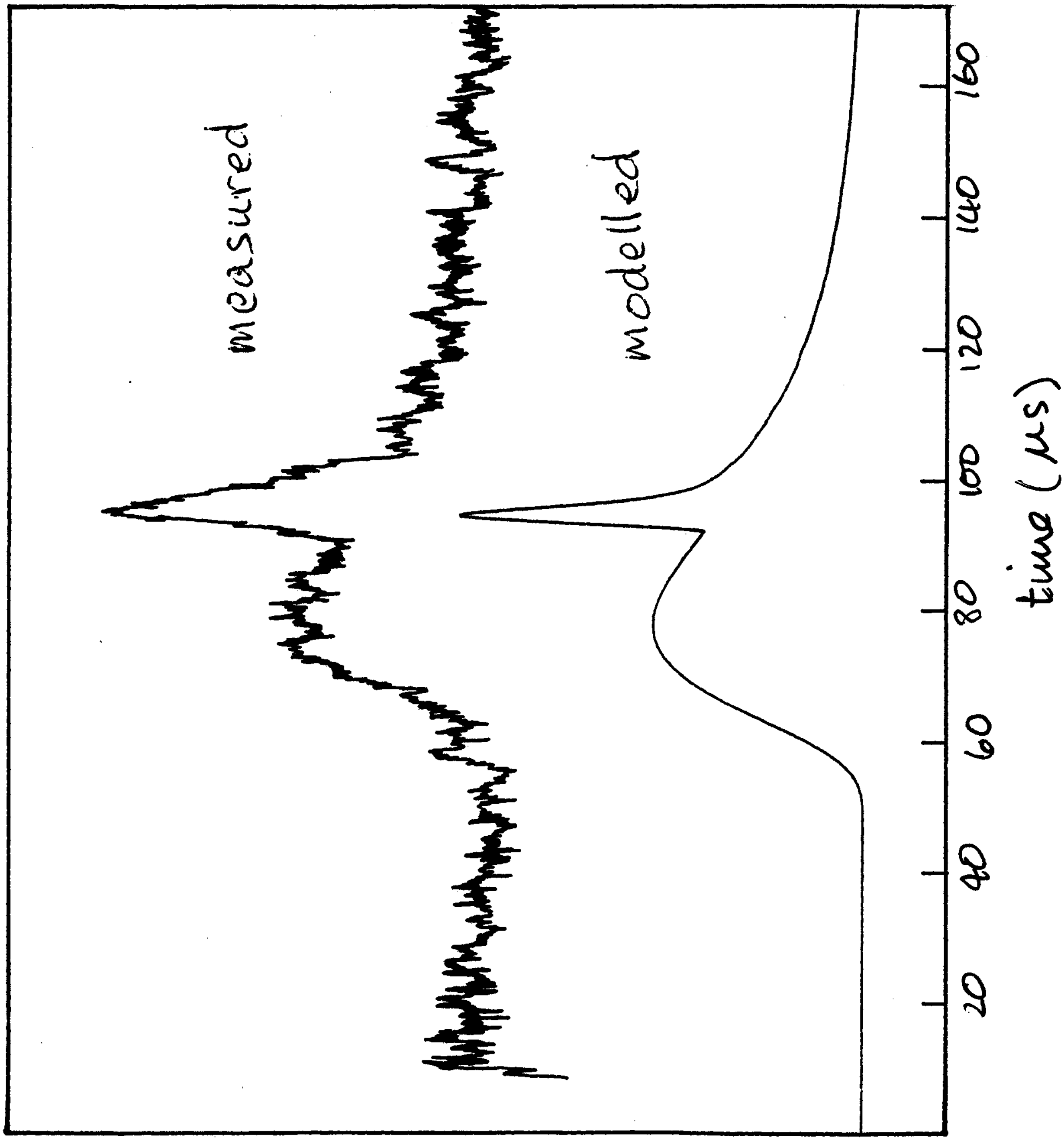
Model

i atom beam temperature 1.4 K

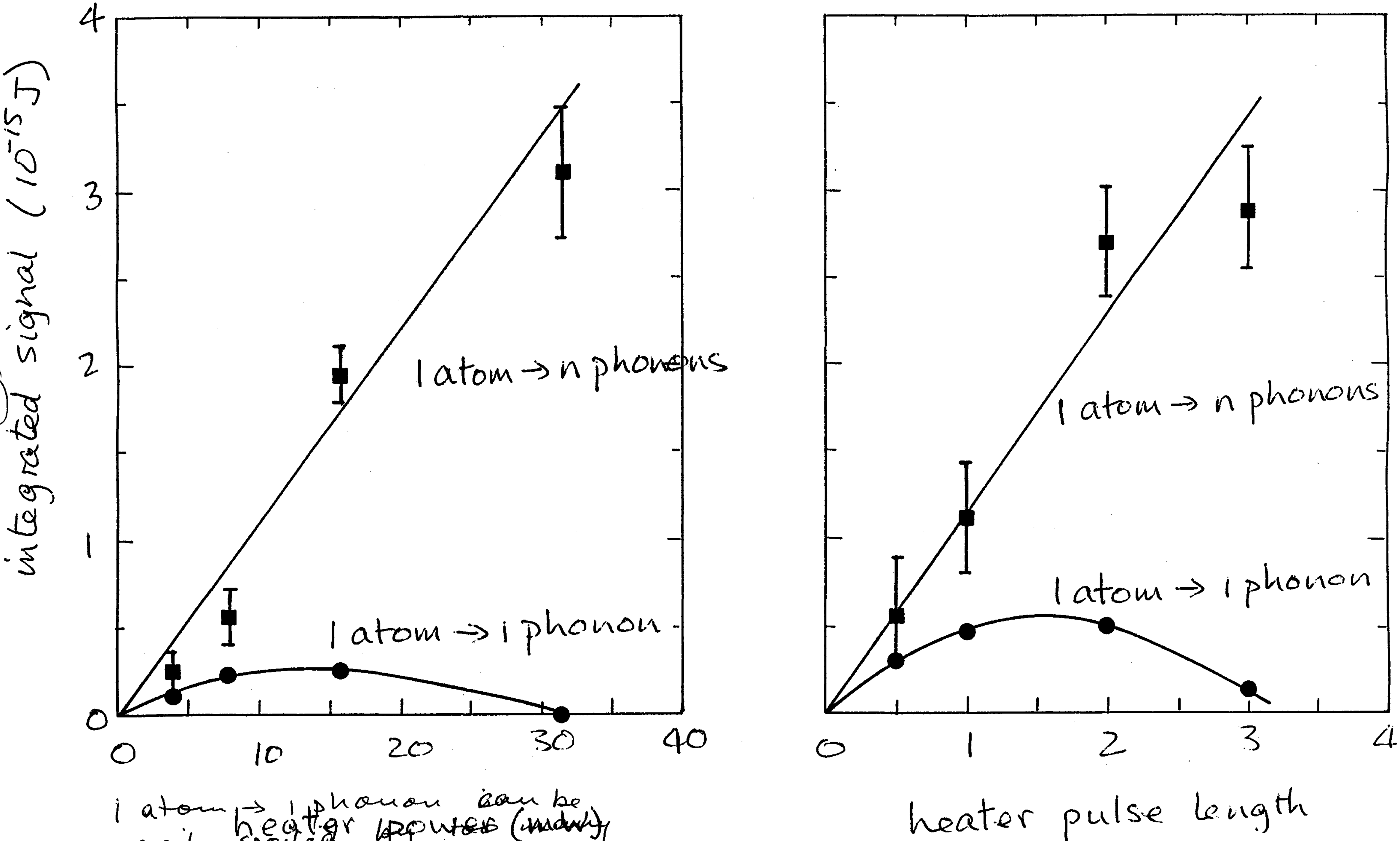
ii essentially δ function input

iii phonons travel at $238\,ms^{-1}$
i.e. fast 3pp decays

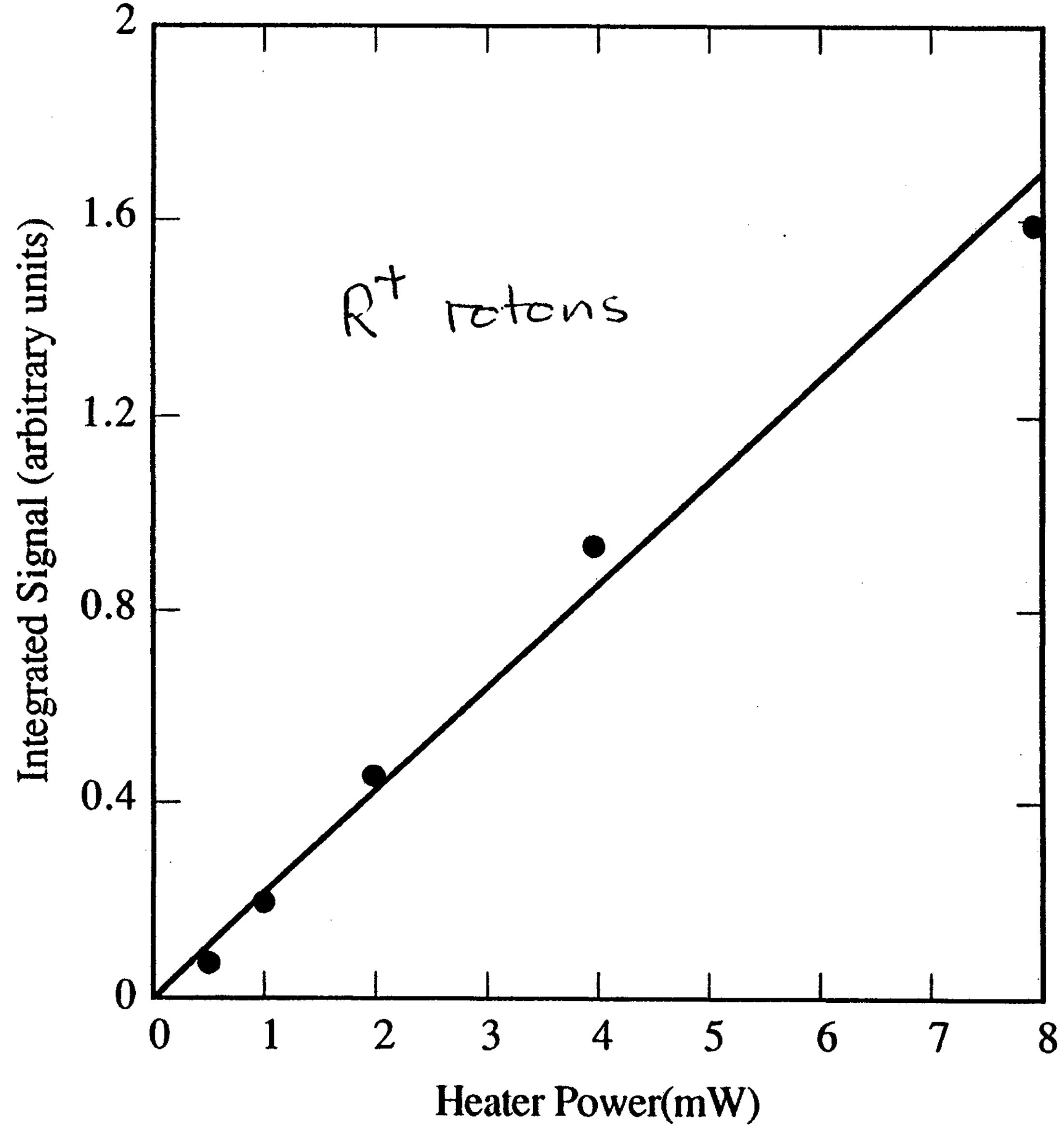
iv all atoms contribute to this signal with equal probability



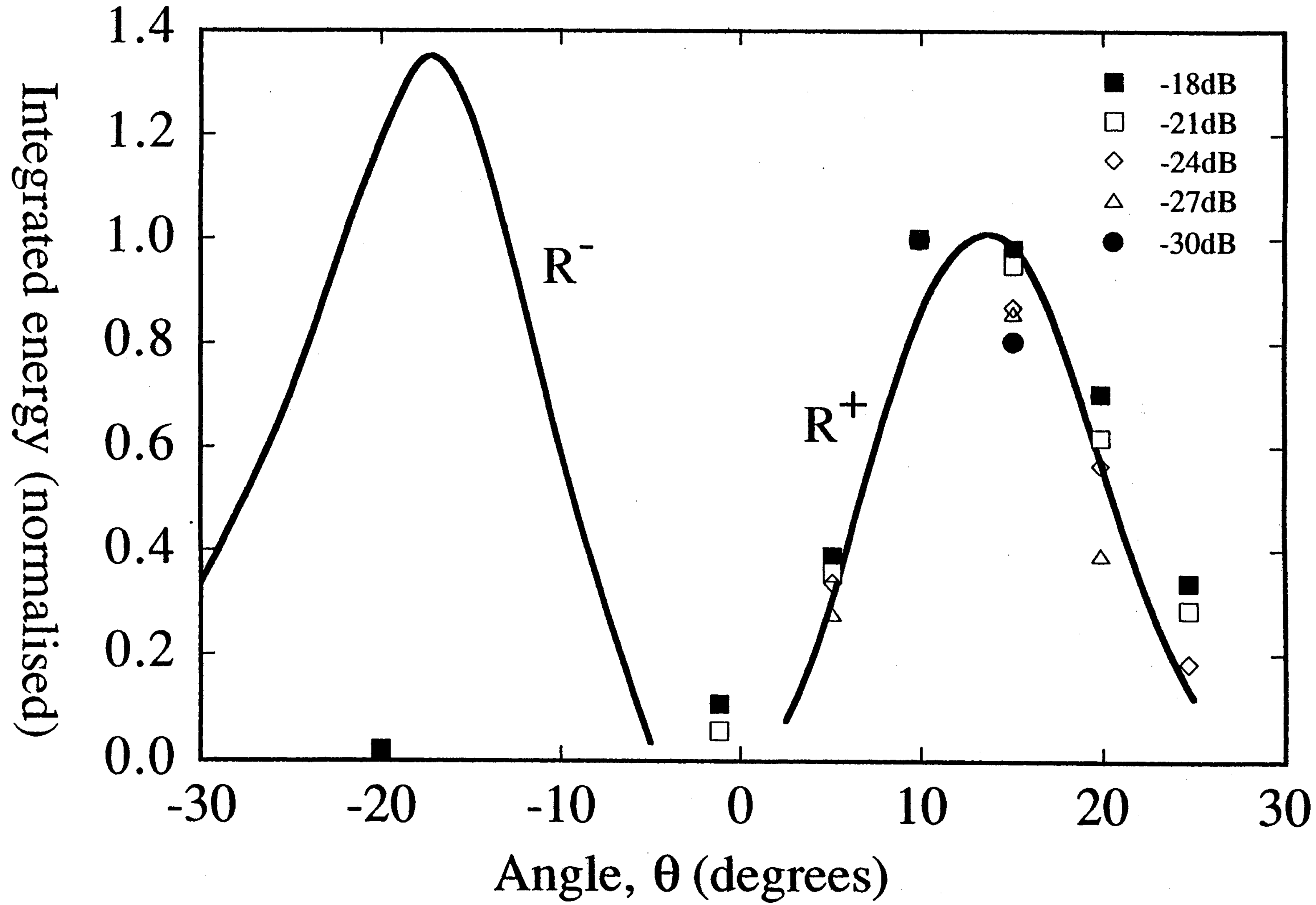
can say it would be
nearer to the normal
because lower energy
phonon has less mo
pro rata than h phono
For future – what
angular dependence
would we expect for the
broad signal?



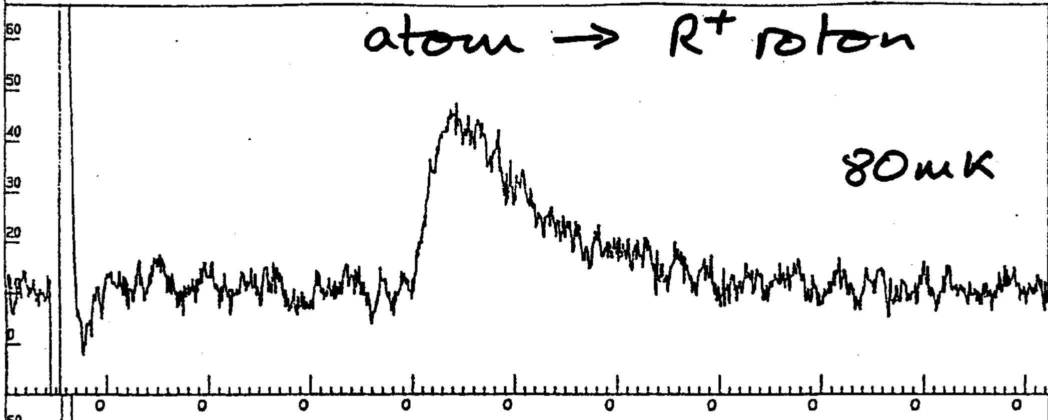
1 atom → 1 phonon can be easily spoiled by atoms hitting the surface.



R^+ rotons
Integrated Signal (arbitrary units)
Heater Power(mW)
0
0.4
0.8
1.2
1.6
2
0
1
2
3
4
5
6
7
8


Integrated energy (normalised)
Angle, θ (degrees)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-30
-20
-10
0
10
20
30
R⁻
R⁺
-18dB
-21dB
-24dB
-27dB
-30dB

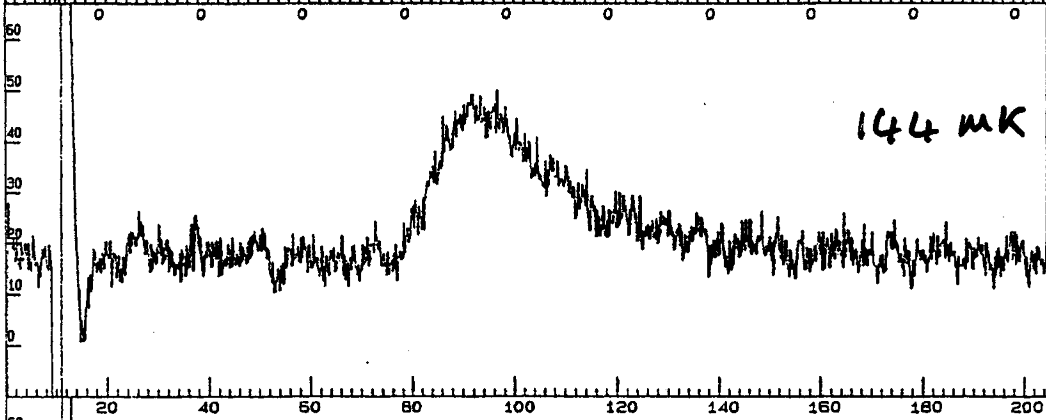
30/10/91 SHEET 1 AFGW



DISK FILE REC379
TRACE NO. 474+475

PW – us
power – dB
Display scale = 8192

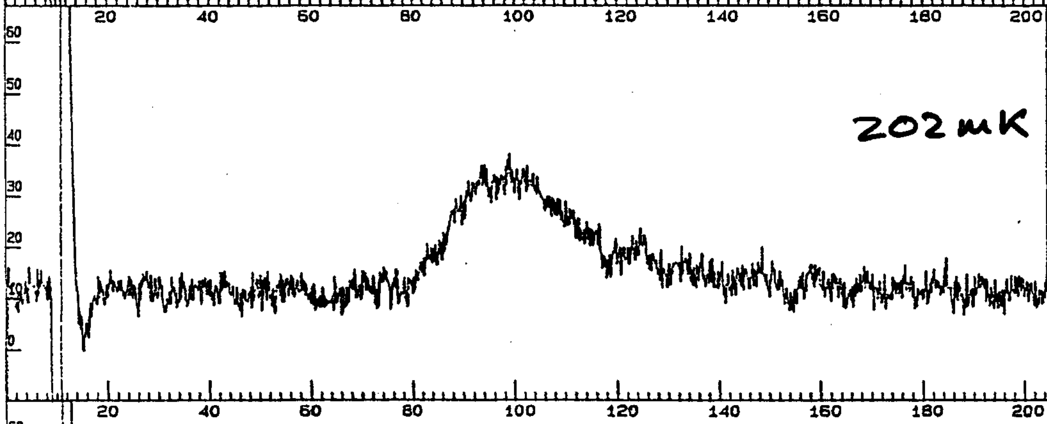
AS –
SI – us
IR – V
IO –
BD –
Temp – Ohms
VO – mV
VOoff – mV
RO – Ohms
magnet cnt = – Amps
Wed, 25 Jul 1990.15:43:49



DISK FILE REC387
TRACE NO. 480+481

PW 2 us
power -27 dB
Display scale = 8192

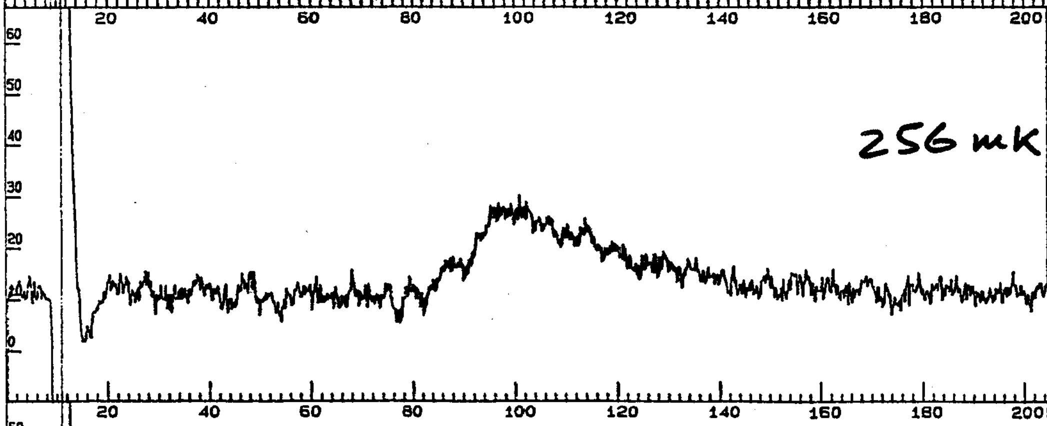
AS 1048576+
SI 0.2 us
IR 0.1 V
IO -0.03
BD 0.0
Temp 48.5 Ohms
VO 5.138 mV
VOoff ~0.100 mV
RO 39 Ohms
magnet cnt = 6.85 Amps
Mon, 30 Jul 1990.16:32:54



DISK FILE REC391
TRACE NO. 482/3/4

PW 2 us
power -27 dB
Display scale = 12416

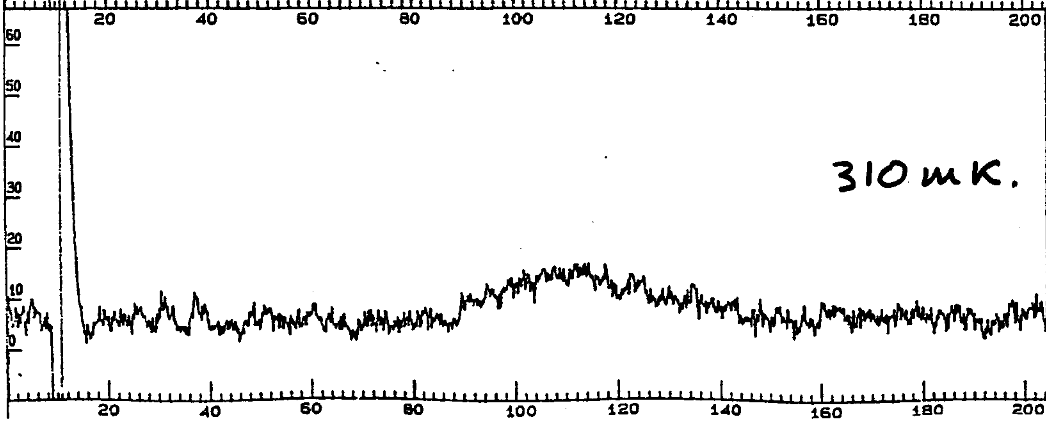
AS 1572864+
SI 0.2 us
IR 0.1 V
IO -0.03
BD 0.0
Temp 39.8 Ohms
VO 5.01 mV
VOoff ~0.09 mV
RO 39 Ohms
magnet cnt = 6.79 Amps
Mon, 30 Jul 1990.19:22:32



DISK FILE REC396
TRACE NO. 485/6/7

PW 2 us
power -27 dB
Display scale = 16384

AS 2097152+
SI 0.2 us
IR 0.1 V
IO -0.03
BD 0.0
Temp 35.1 Ohms
VO 5.08 mV
VOoff ~0.09 mV
RO 39 Ohms
magnet cnt = 6.665 Amps
Mon, 30 Jul 1990.21:59:50



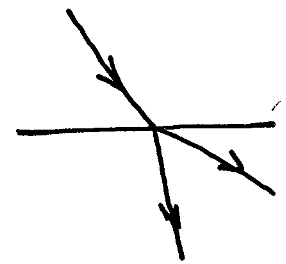
DISK FILE REC401
TRACE NO. 489/90/

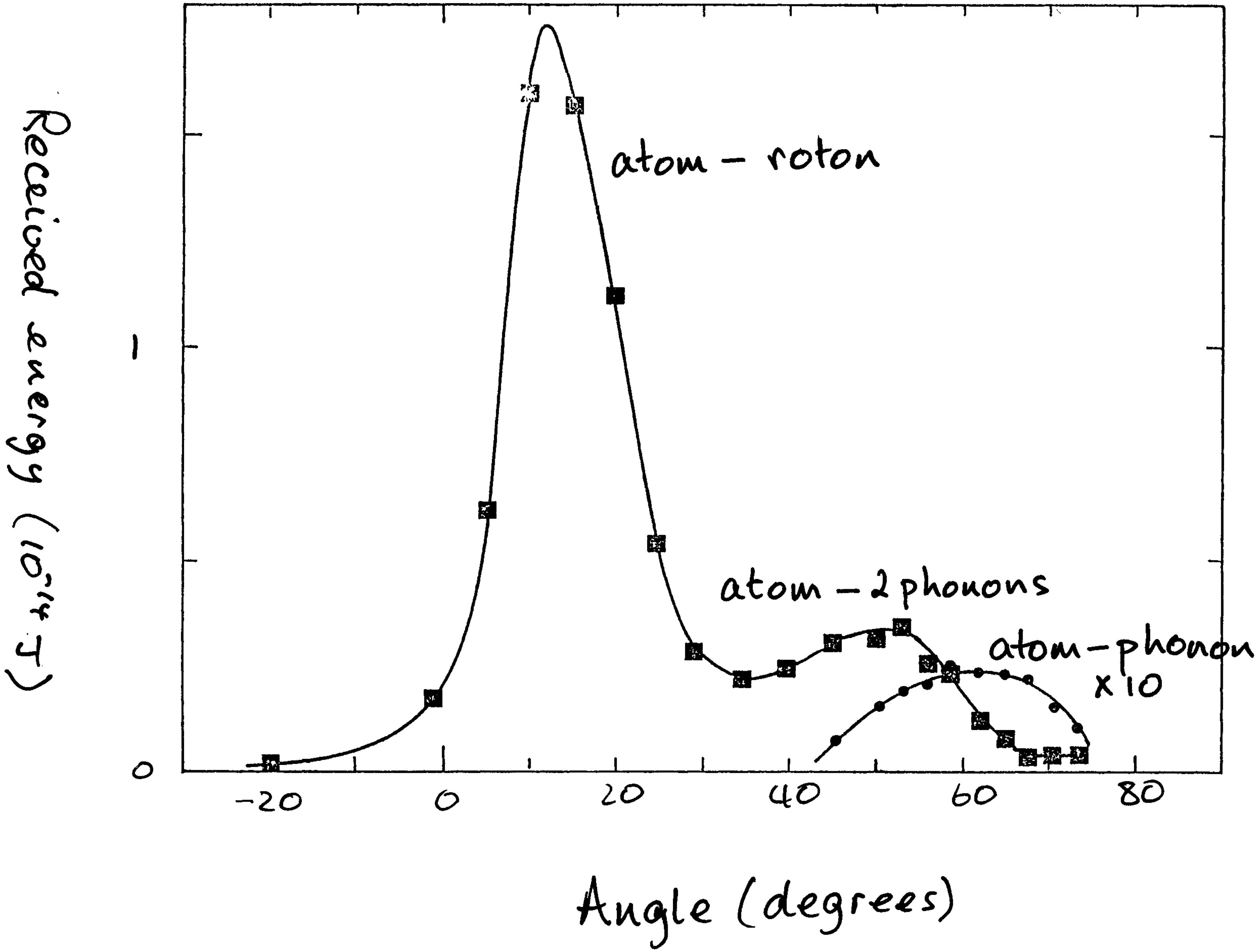
PW 2 us
power -27 dB
Display scale = 16384

AS 2097152+
SI 0.2 us
IR 0.1 V
IO -0.03
BD 0.0
Temp 31.8 Ohms
VO 5.03 mV
VOoff ~0.11 mV
RO 39 Ohms
magnet cnt = 6.50 Amps
Tue, 31 Jul 1990.17:54:31

Condensation

Brown & Wyatt

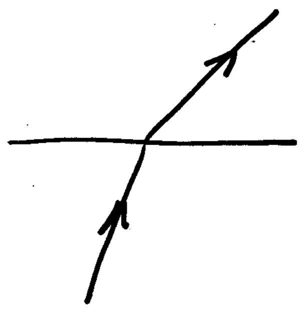




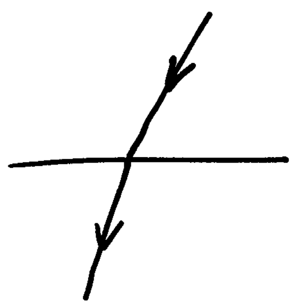
Quantum Evaporation, condensation and reflection at the surface of liquid ^4He

Adrian Wyatt
University of Exeter, UK.

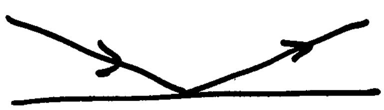
Quantum Evaporation:



Condensation:

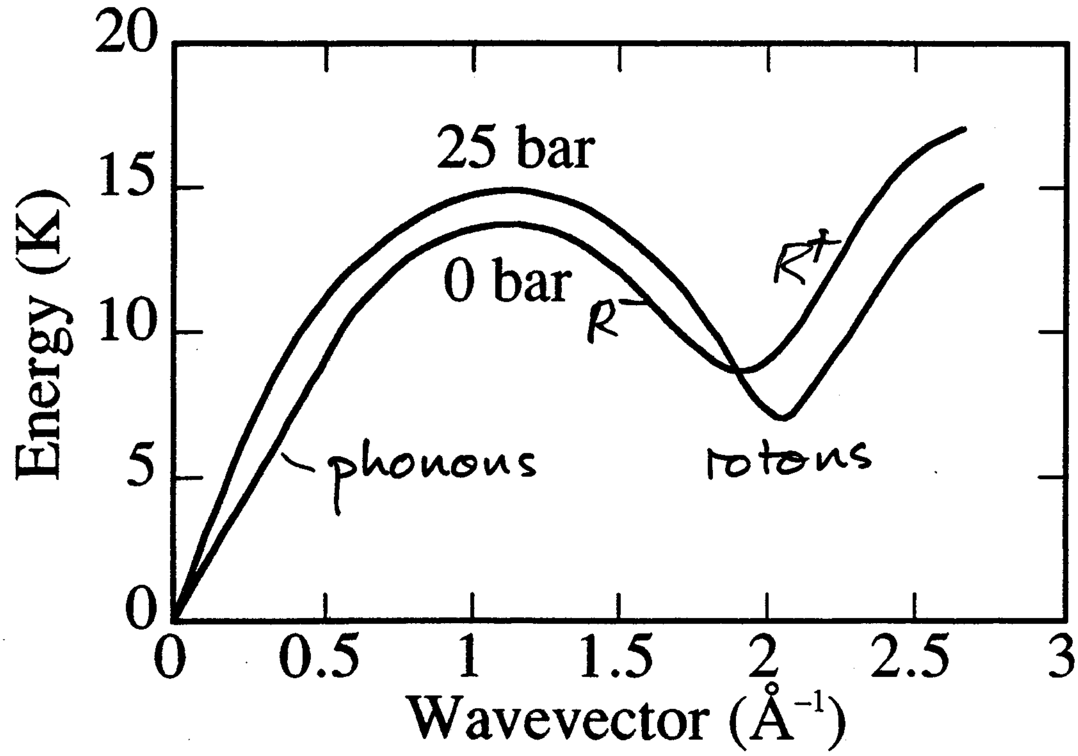


Reflection:



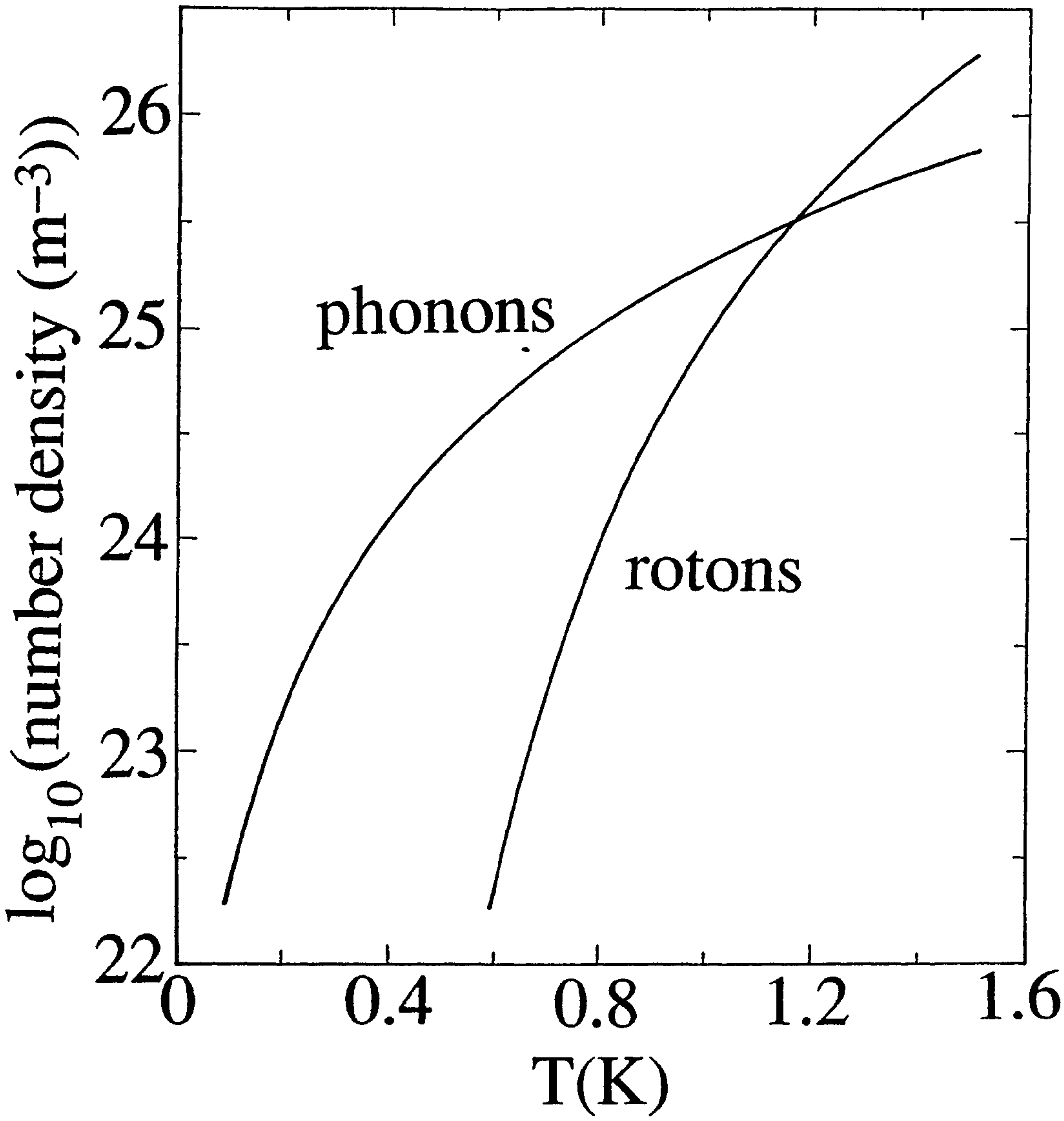
^{4}He dispersion curve

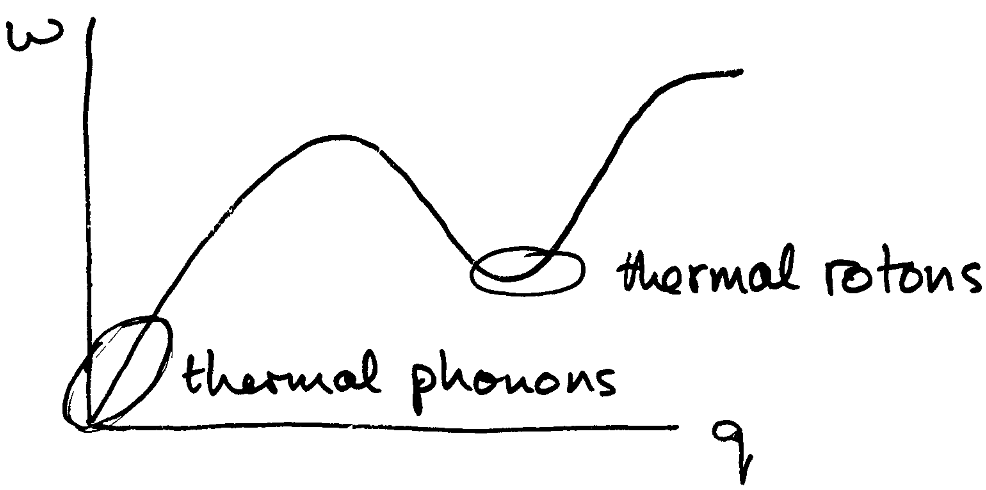
fig2



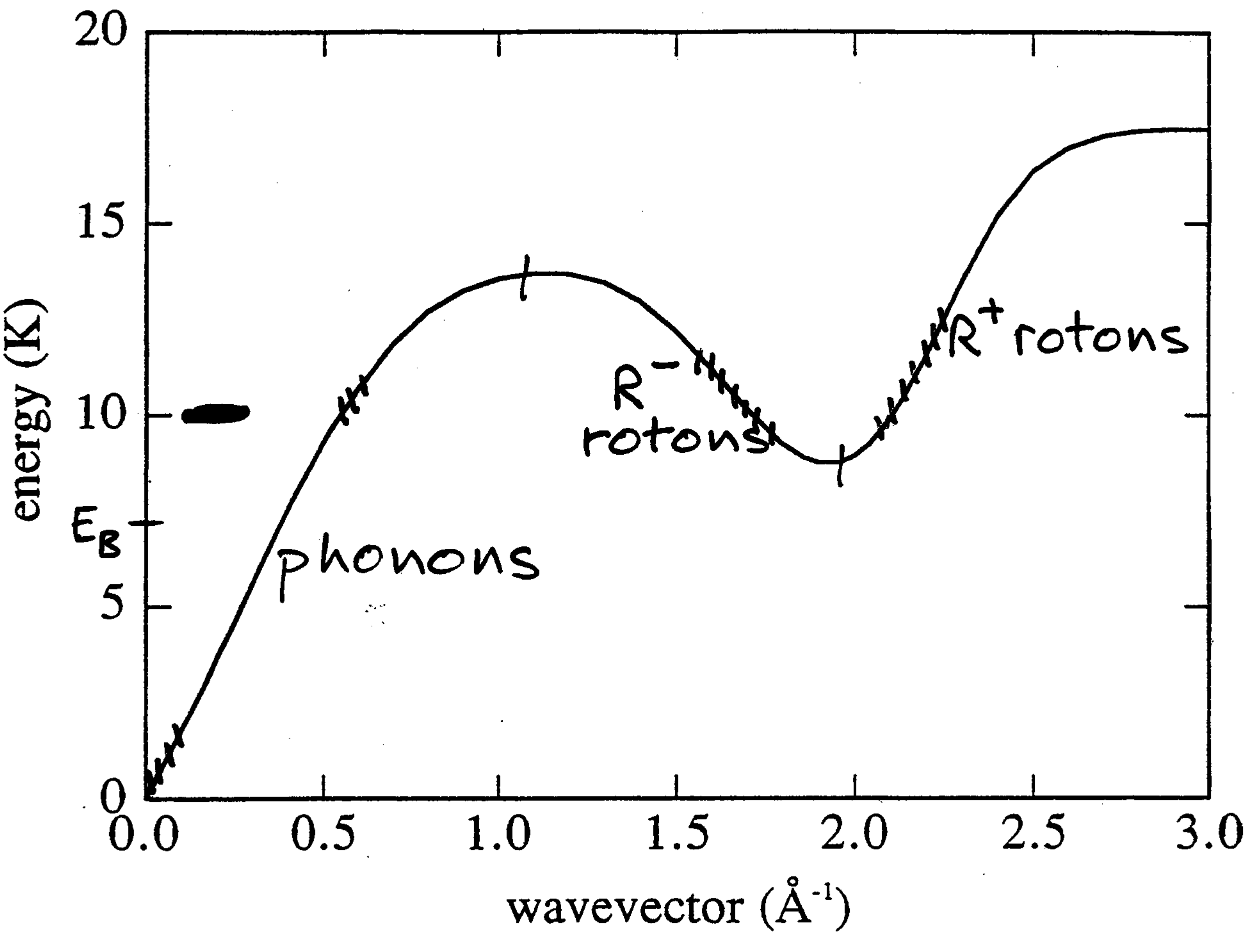
excitations are extremely well-defined

P=0


26
25
24
23
22
0
0.4
0.8
1.2
1.6
T(K)
$\log_{10}$(number density (m^{-3}))
phonons
rotons


ω
q
thermal rotons
thermal phonons

Excitations in liquid ^4He at $P=0$



$\omega(q)$ is measured by neutrons

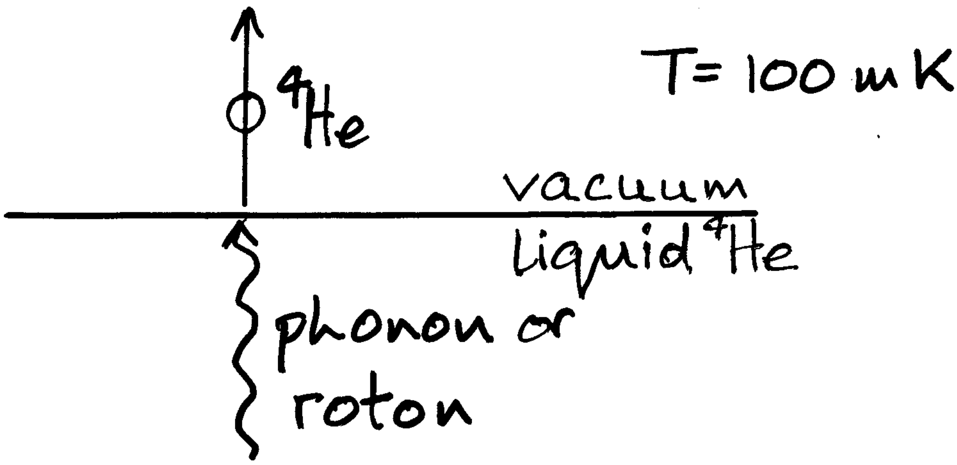
can create beams of ballistic excitations

note: atoms are not excitations

need for R^+ sig v's t

Quantum Evaporation

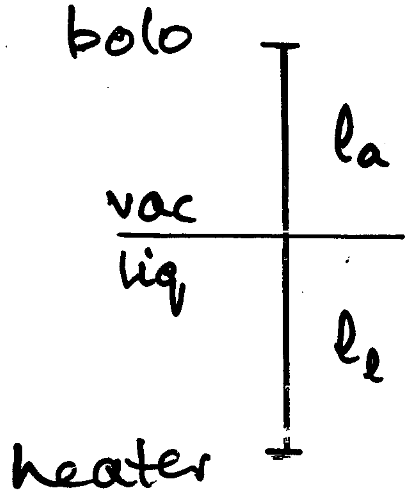
it is analogous to the photo electric effect



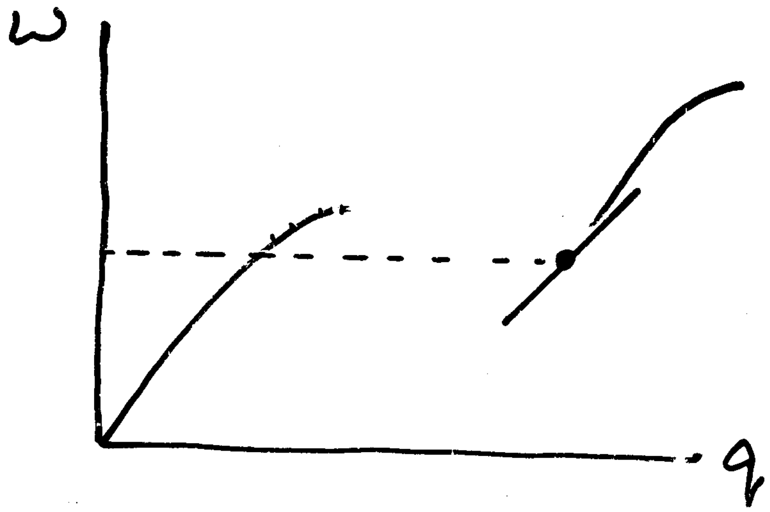
a phonon or roton is annihilated and a free atom is created

$$\hbar\omega = E_b + \frac{p^2}{2m}$$

measure the total time of flight



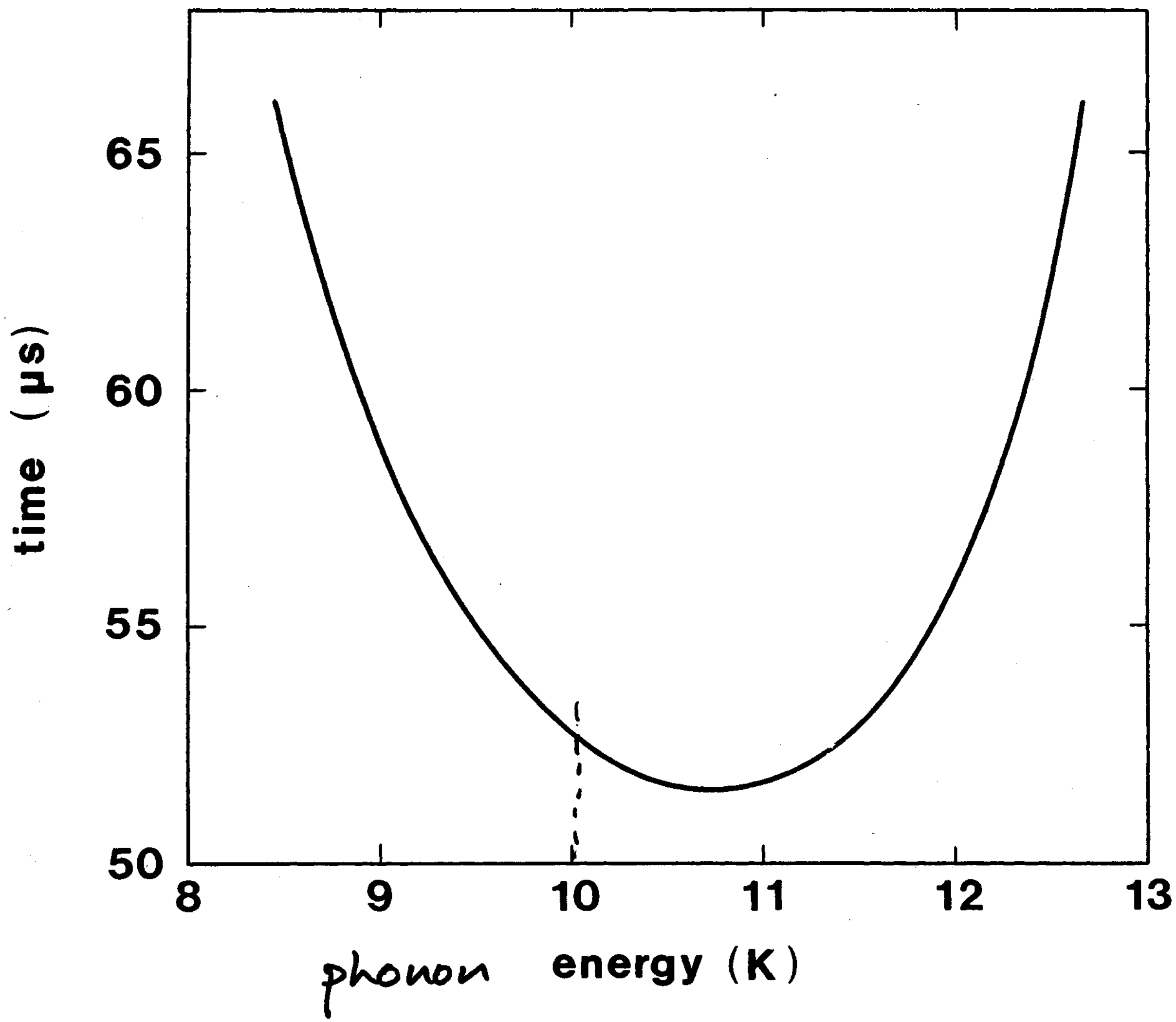
$$t_{total} = \frac{l_l}{V_g(\omega)} + \frac{l_a}{V_a}$$



$$\hbar\omega = E_B + \frac{1}{2} m_4 V_a^2$$

$$E_B = 7.16 \text{ K}$$

total time of flight

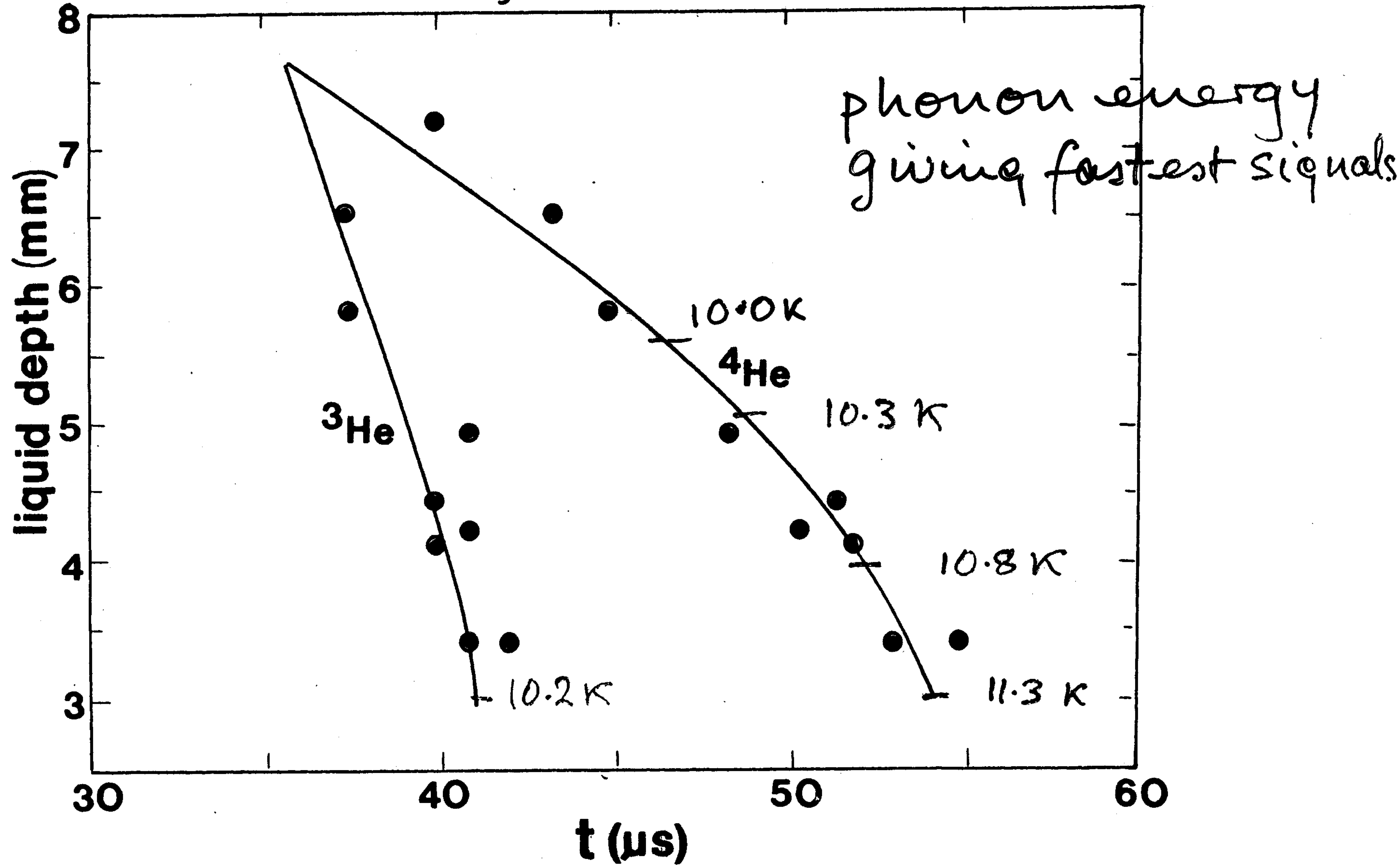


for 1 liquid depth...

57.84.

Fermi energy corrected.

early result



^{3}He on the surface of liquid ^{4}He

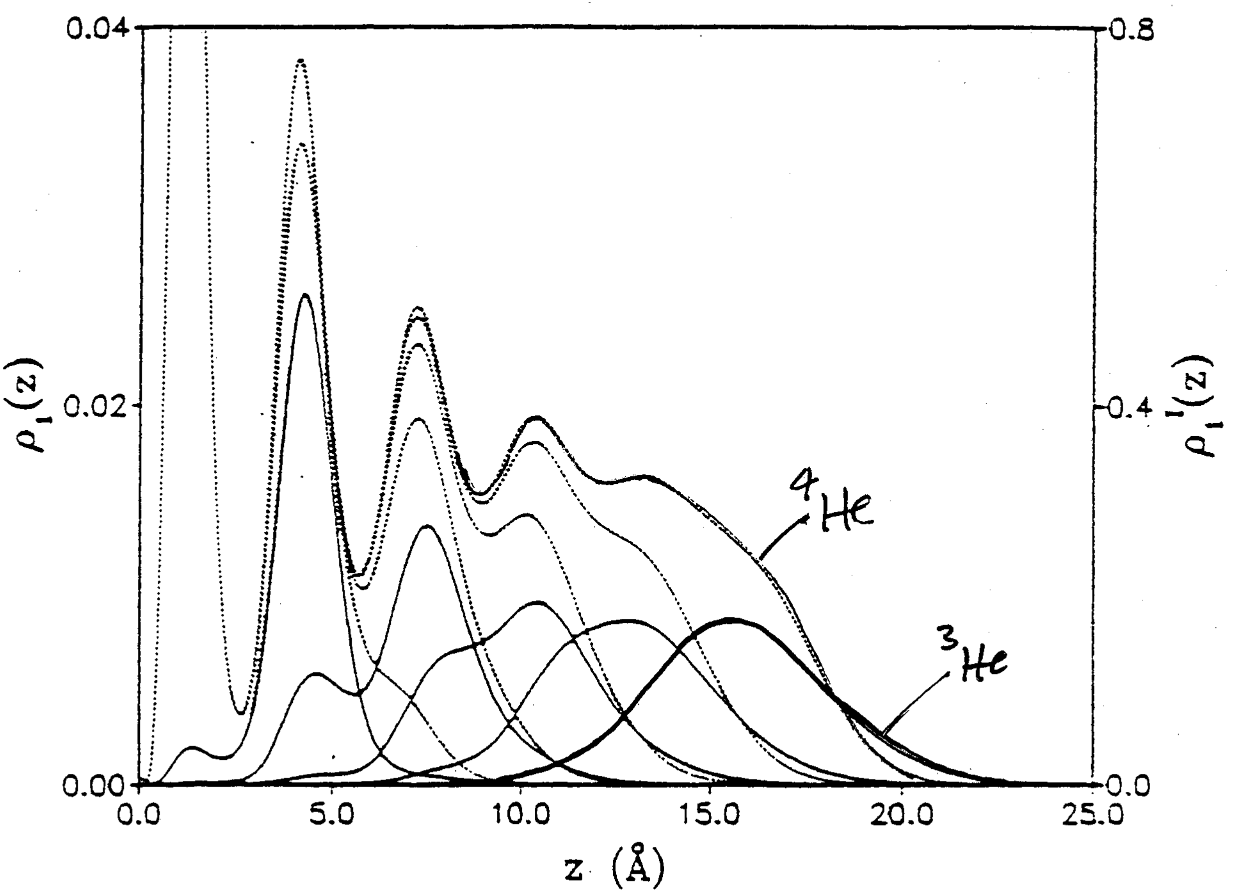


FIG. 1. The density $\rho_1(z)$ of the background film of ^{4}He atoms (dotted lines, scale on left abscissa) and of the ^{3}He impurity $\rho_1^I(z)$ (solid lines, scale on right abscissa) for surface coverages of $n = 0.15$, 0.20, 0.25, 0.30, and 0.35 ^{4}He atom/Å^2. The ^{4}He densities of all films shown are indistinguishable within the first, and partly within the second, layer. The ^{3}He-impurity density is normalized such that $\int dz\, \rho_1^I(z) = 1$. This figure is an extended version of a similar figure of Ref. 4.

ref Krotscheck et al

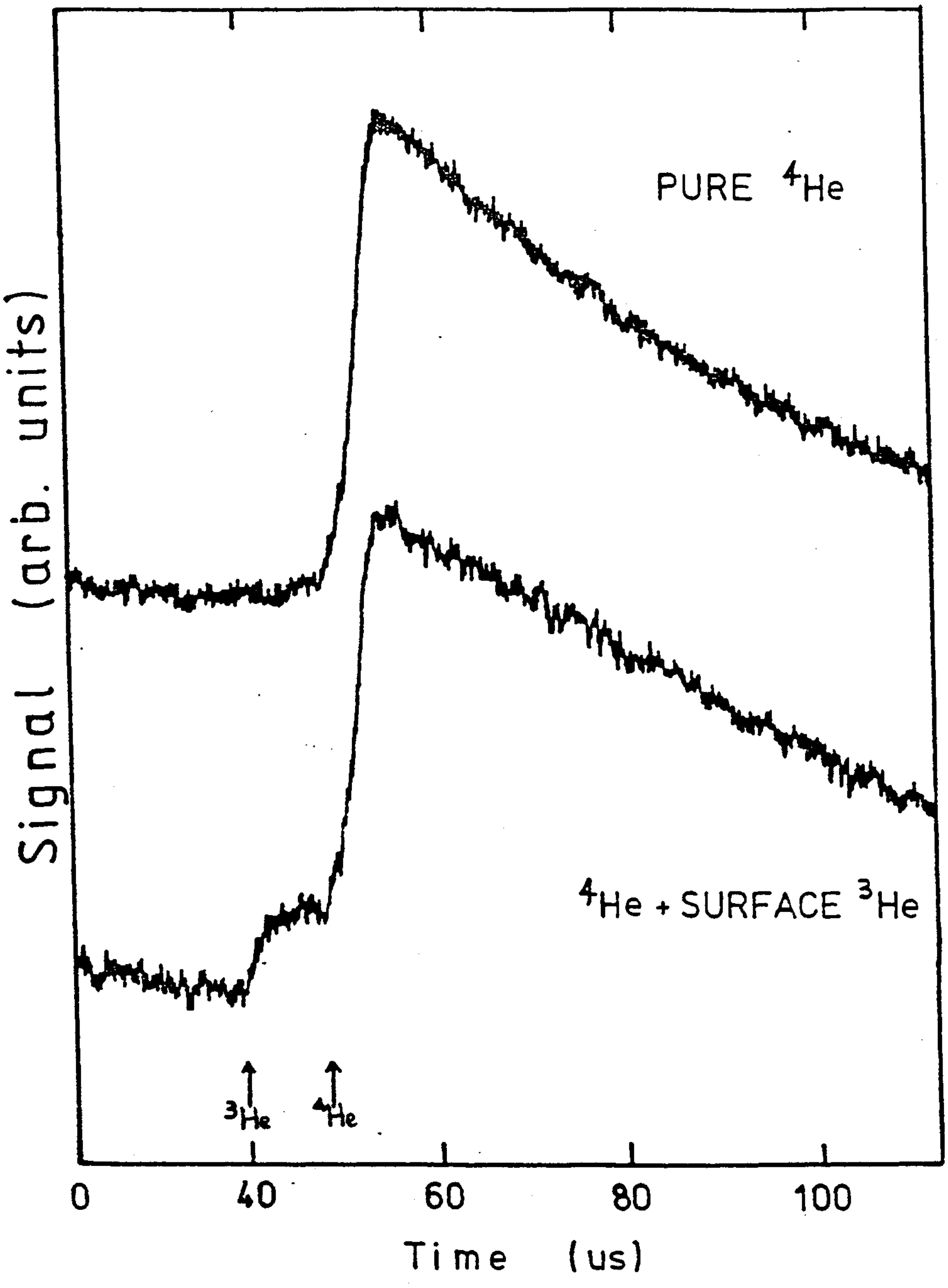
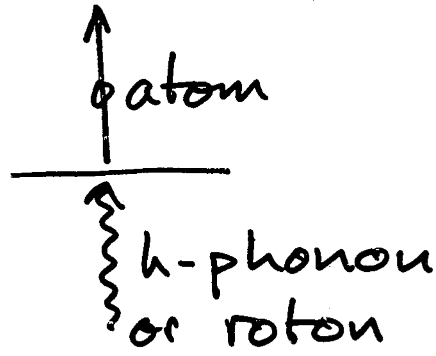
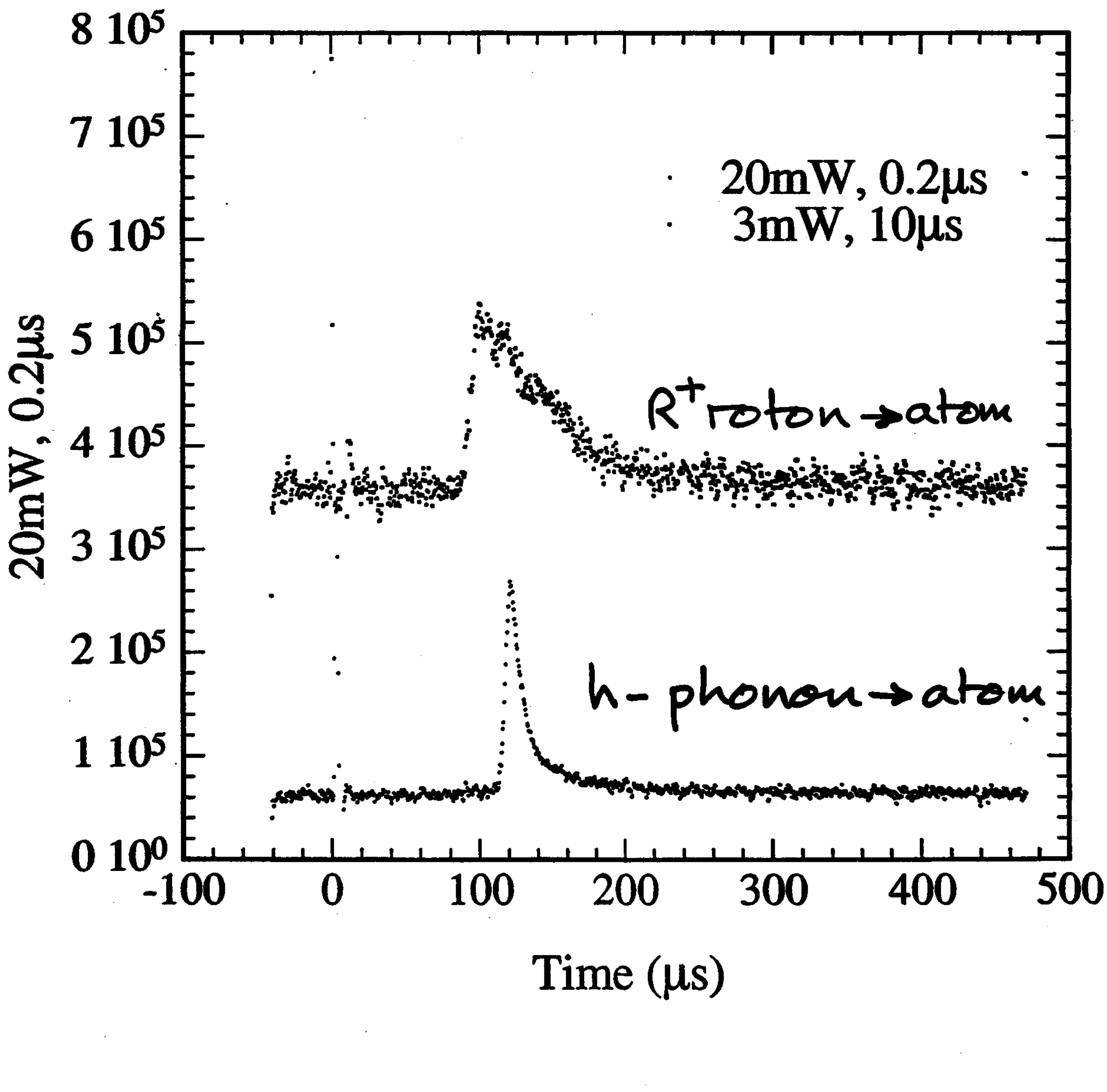


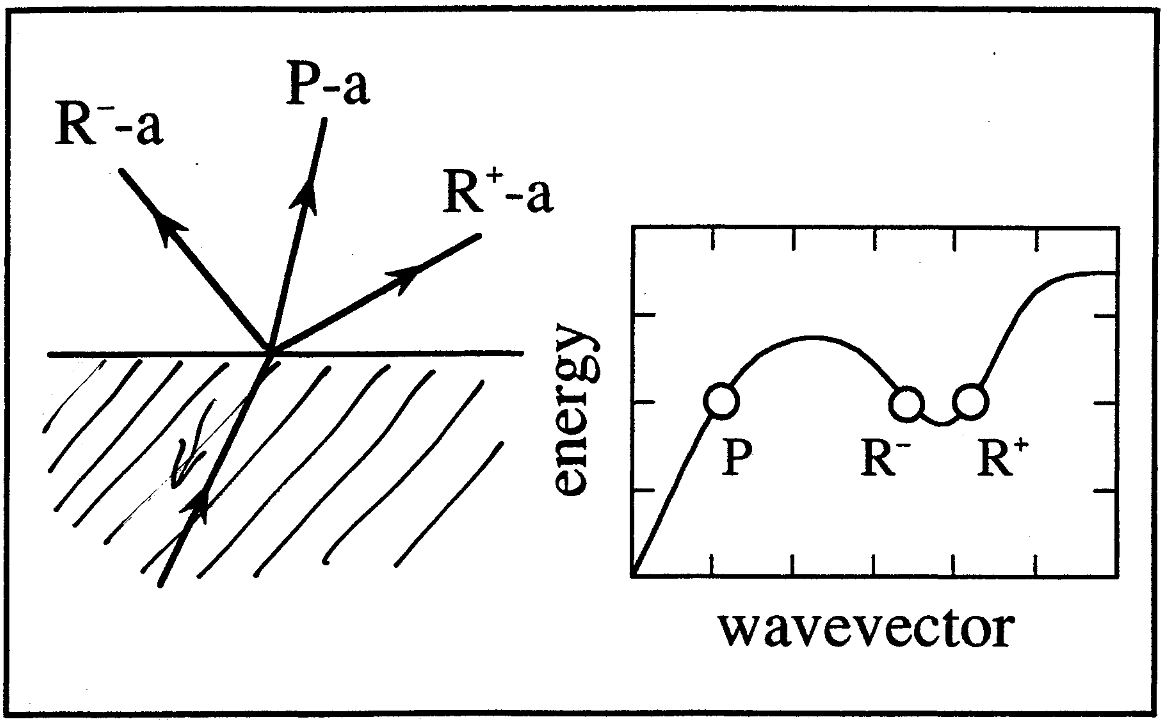
FIGURE 5.10 : Example of a measured desorbed atom pulse before and after the addition of ~0.23% of a monolayer of ^{3}He atoms to the ^{4}He surface. For the upper trace less than 0.1% of a ^{3}He monolayer was present. Liquid depth is 4.3mm, 1us, -13.3dB input power.





go back to 'Excitations in liq 4He'

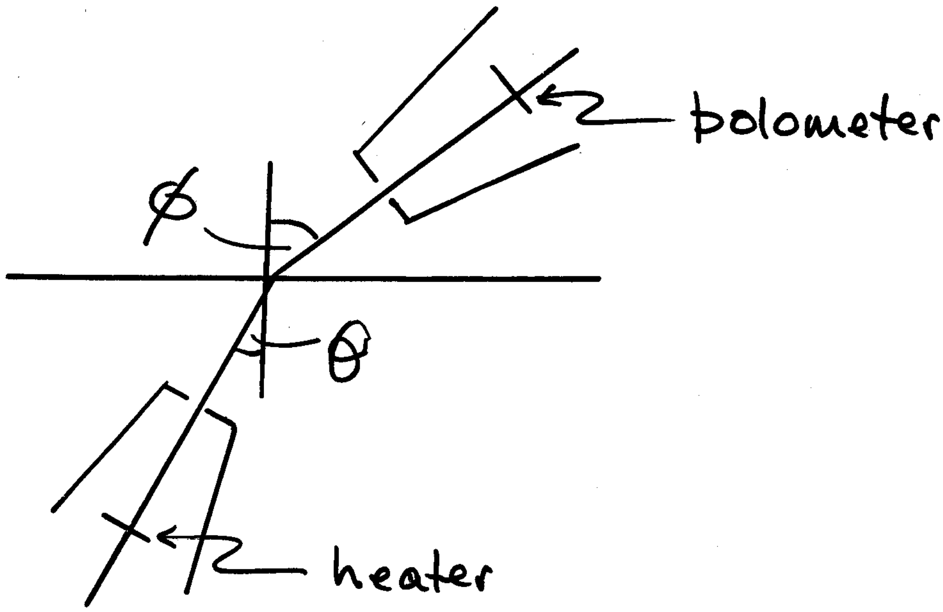
angle of evaporation



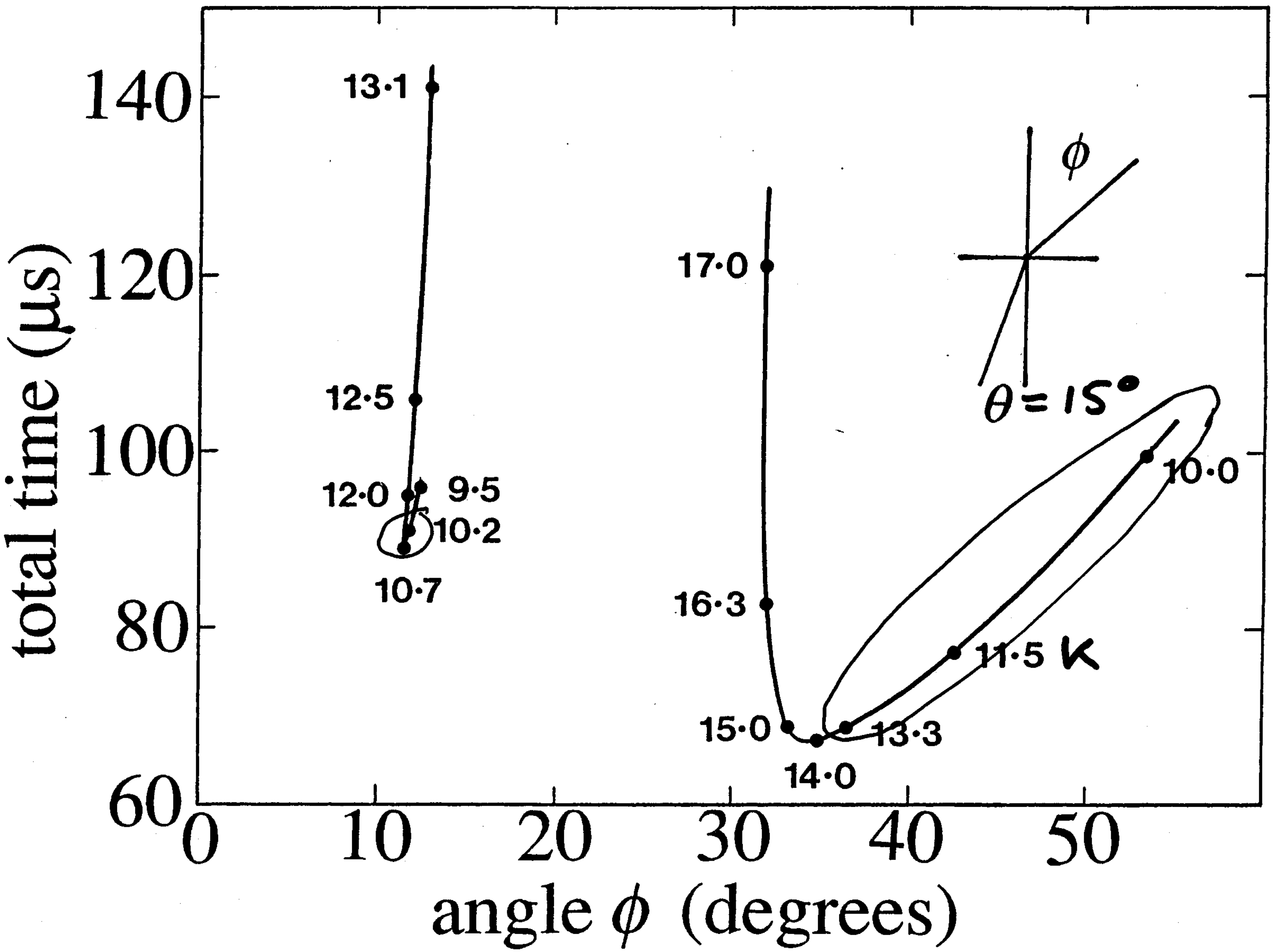
$$q_{\parallel} = k_{\parallel}$$

excitation — atom

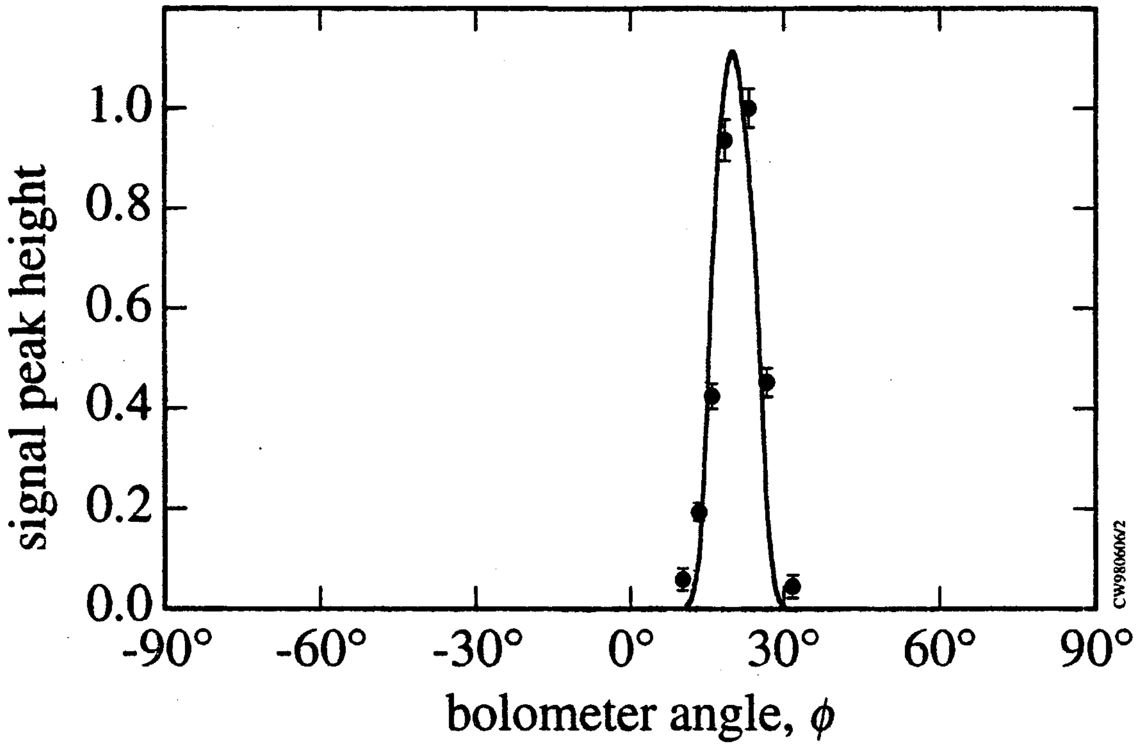
Apparatus.

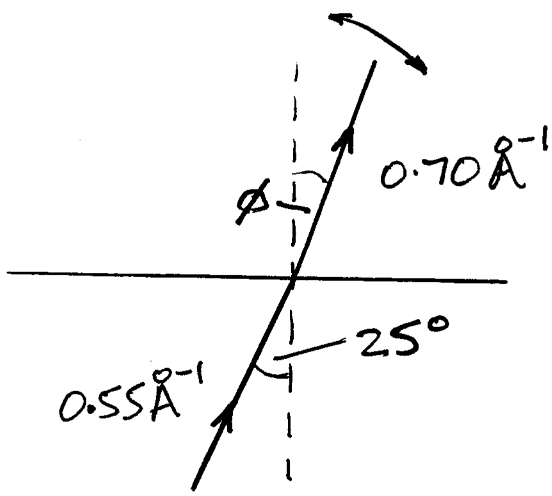


calculation



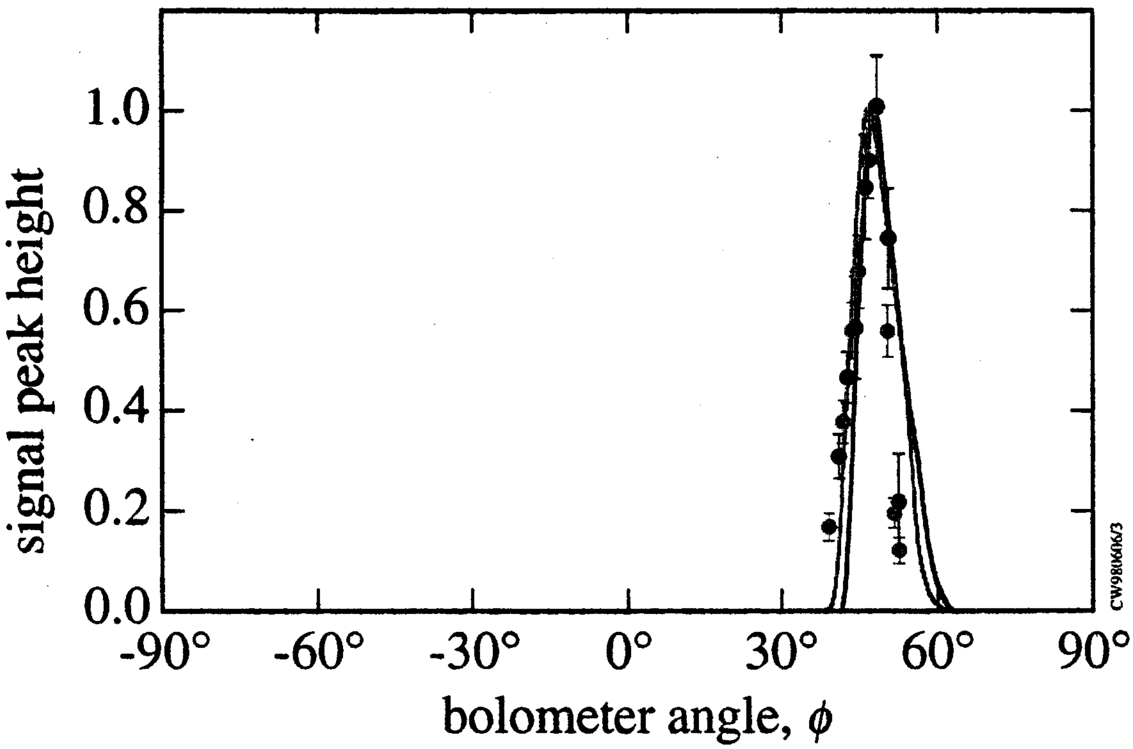
Phonon Evaporation

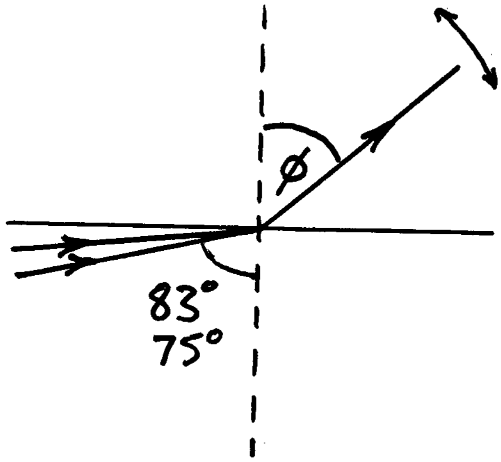




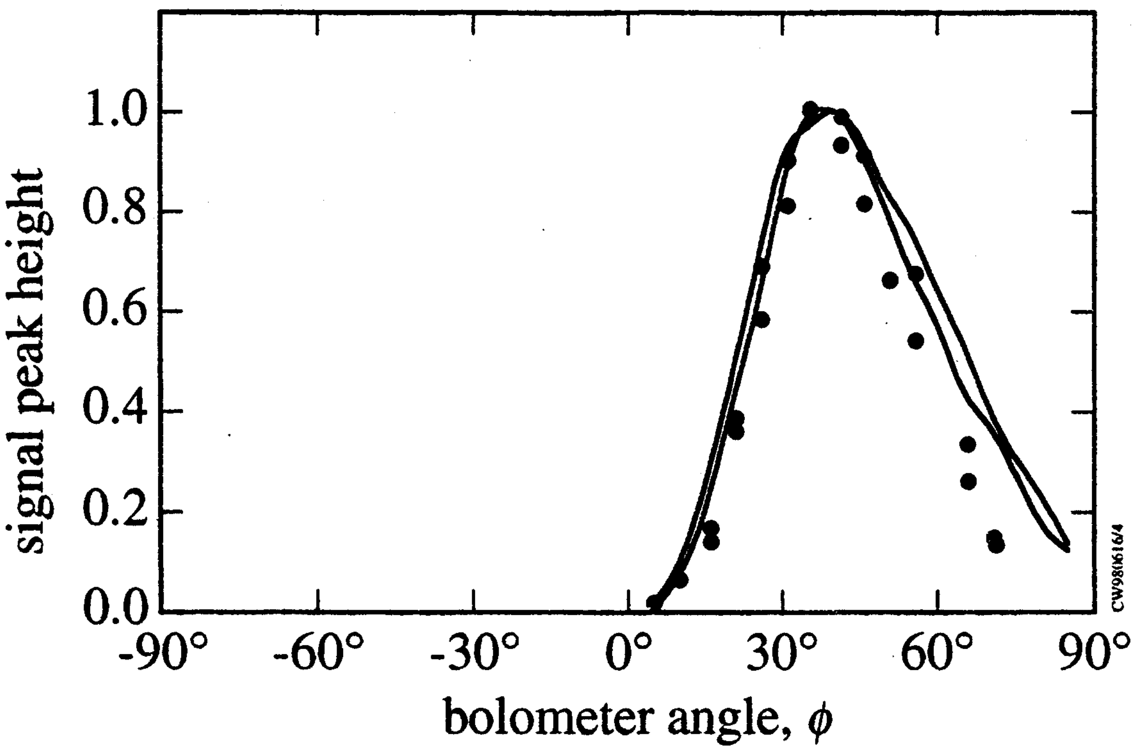
$$q_{\parallel} = k_{\parallel}$$

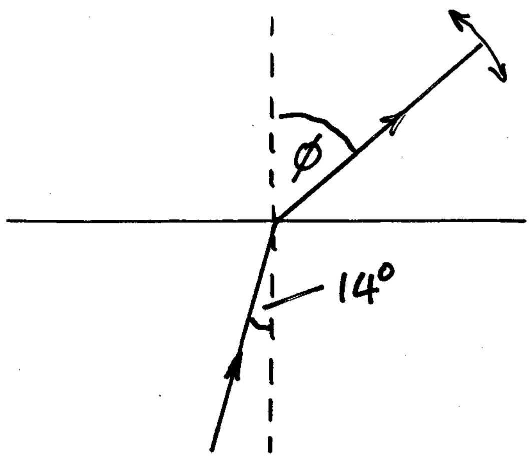
Phonon Evaporation





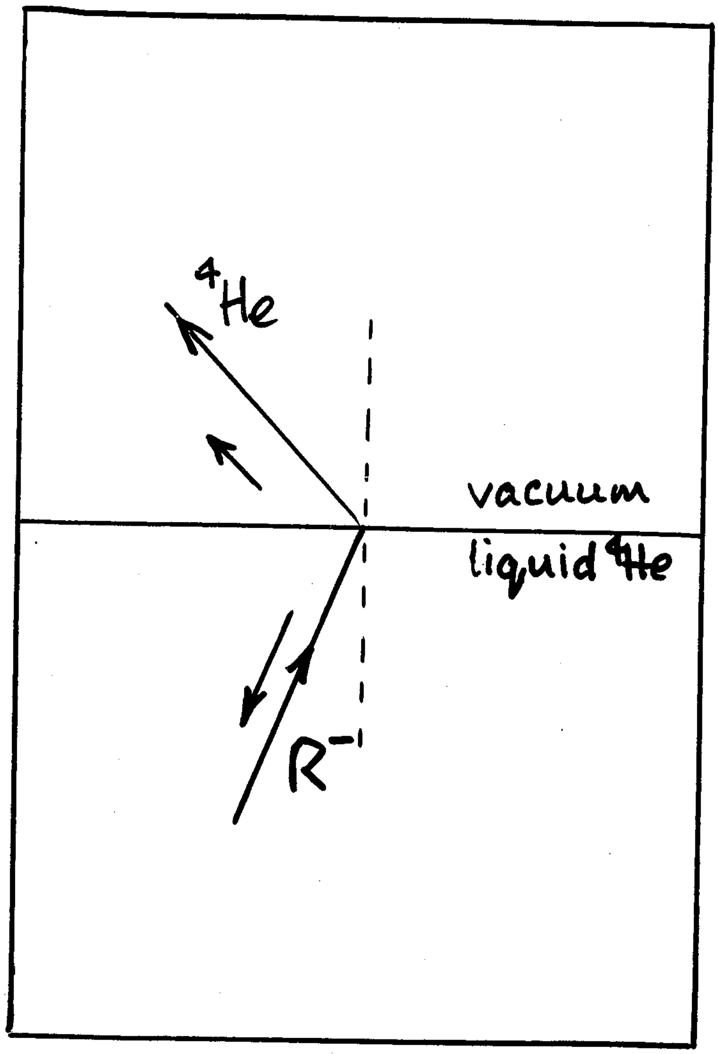
R^+ Roton Evaporation





ref Charles Williams

Quantum evaporation by R⁻ roton

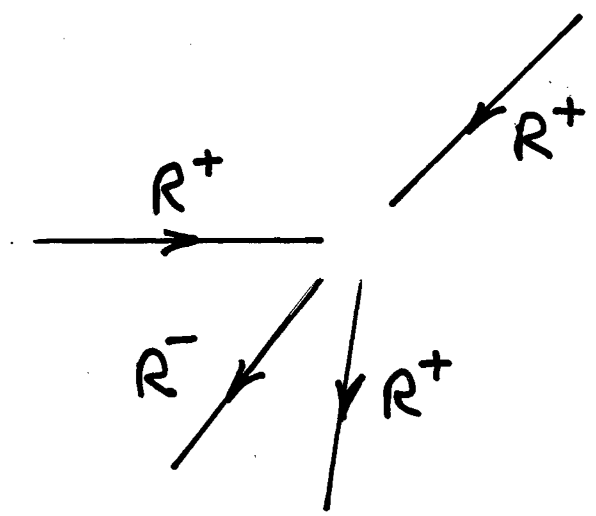


This is what we expect
but saw nothing.
We are using the surface
like the tennis racquet to
measure the reaction.

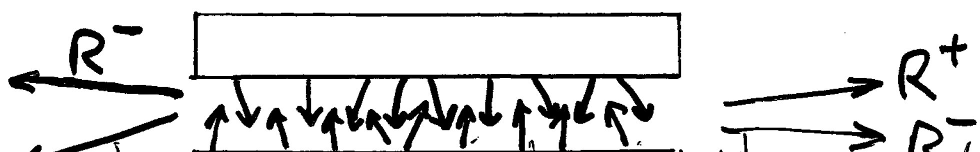
Source of R⁻ rotons

they must be produced by roton-roton scattering,
they cannot be injected by a heater

$$R^+ + R^+ \leftrightarrow R^+ + R^-$$



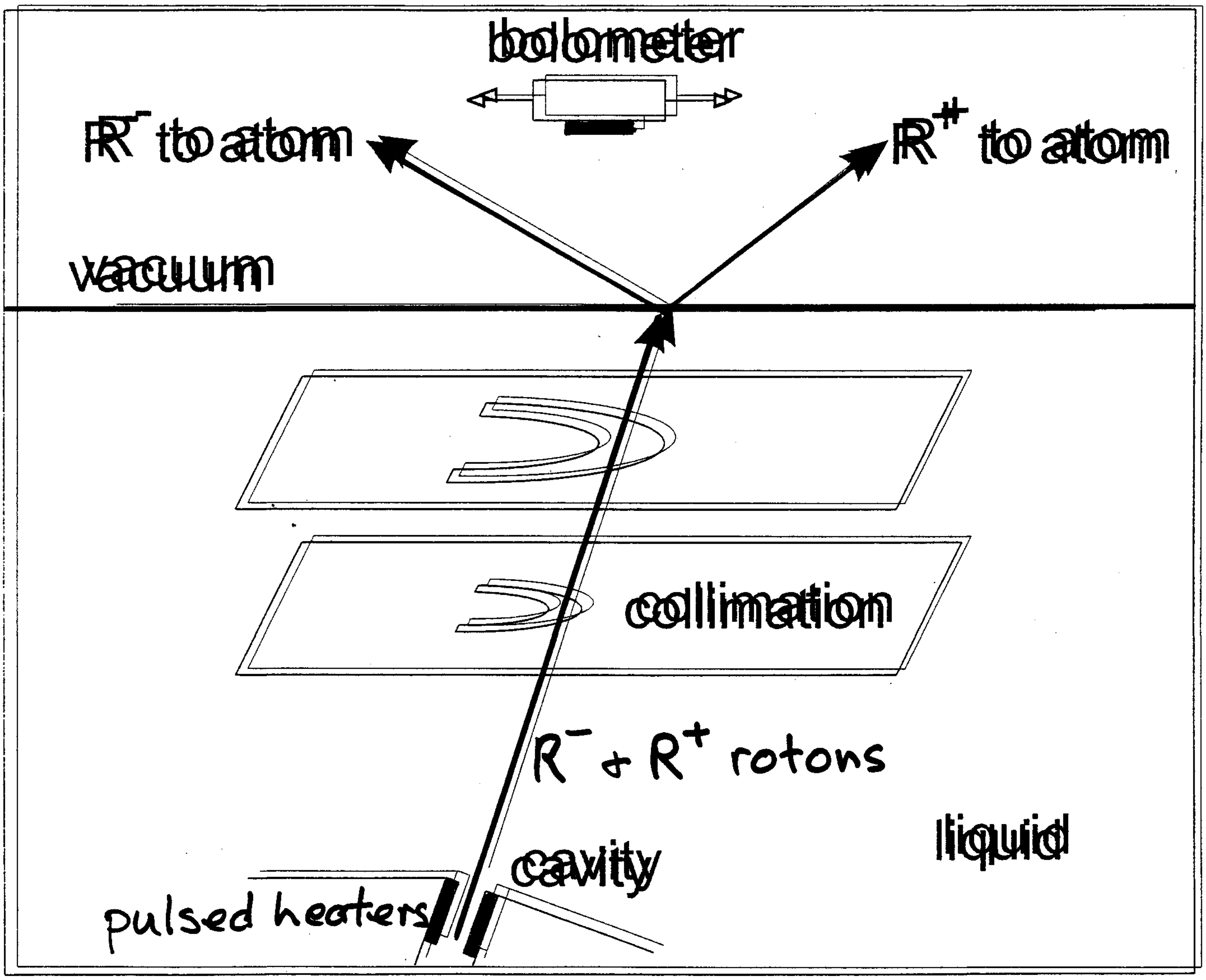
to increase the probabablity of R+ roton scattering a cavity is needed



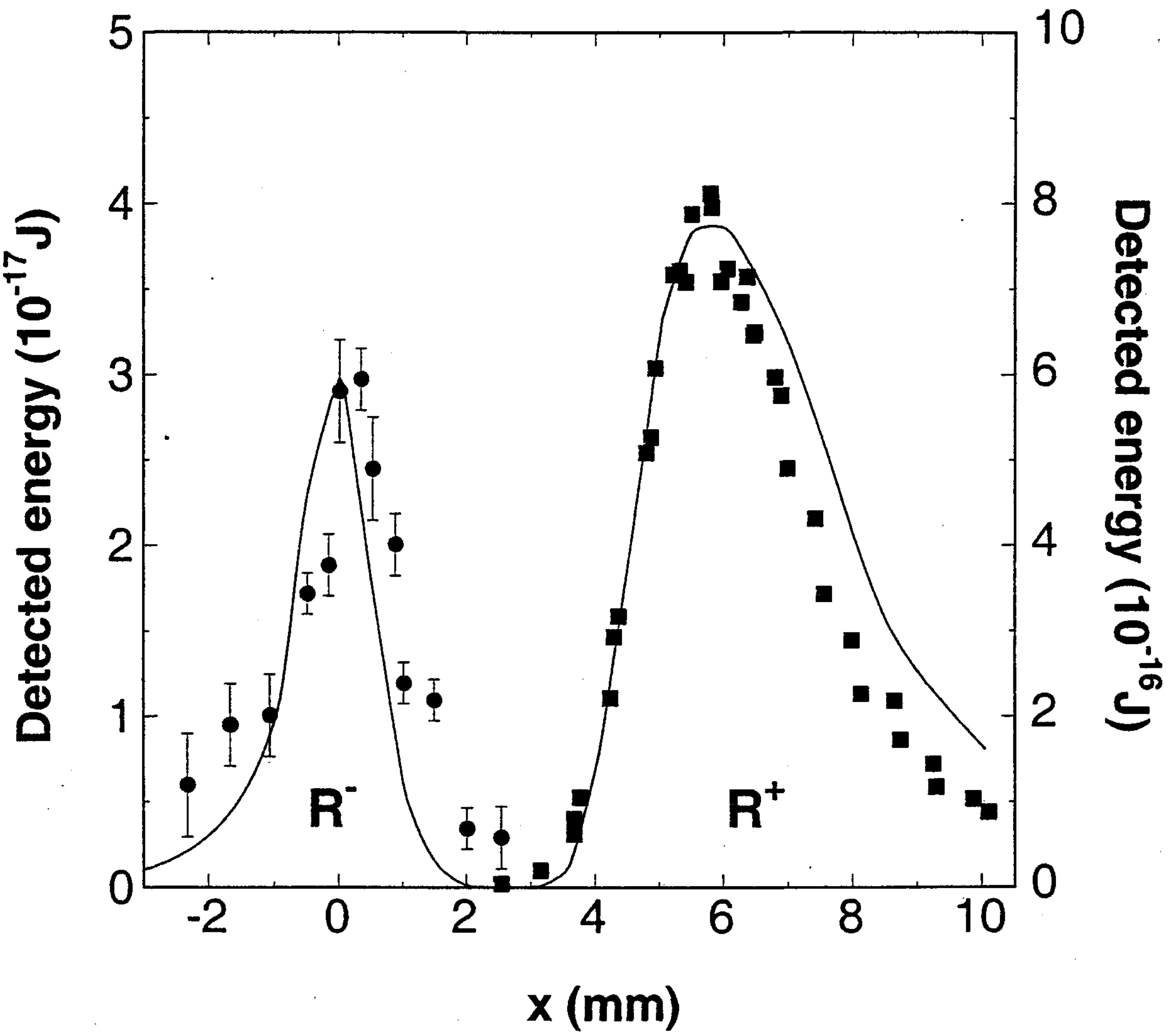
R⁻ rotons exist in thermodynamic equilibrium so must be produced in the liquid & not at boundaries

Cavity must be small.

Experimental arrangement to detect the R^- roton.



Experimental result:
atom flux from quantum evaporation by R^- and R^+ rotons



position of atom detector

So the long quest to find these particles is over
We know that they are created by interactions within the liquid He which is unlike these R^+ rotons which are created at solid-liquid interface.

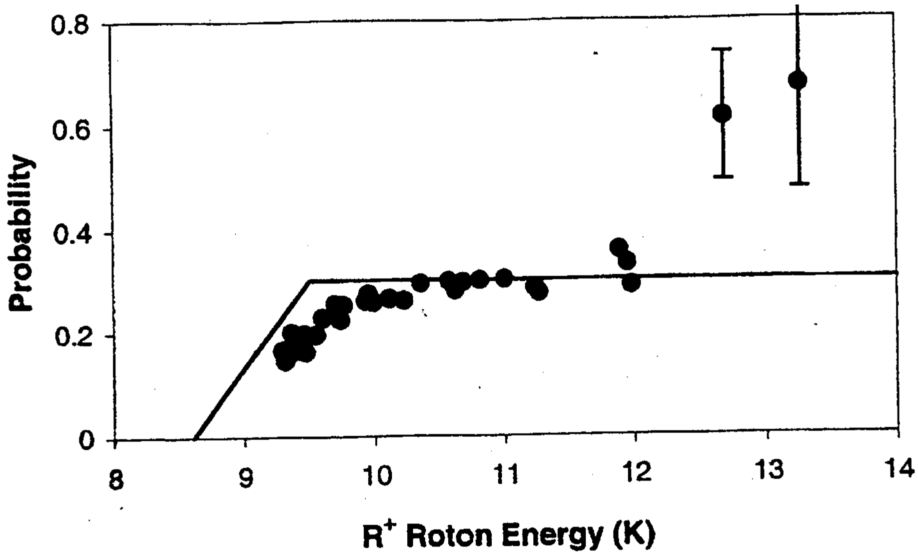


Fig. 2. Evaporation probability for R^+ rotons as a function of roton energy. The vertical scale is set to be in approximate agreement with experimental measurements of averaged probabilities. Error bars are drawn for two points to illustrate the uncertainty in the increase of P_{+a} at high energy. Solid curve: a fit to $E < 12K$ data using a saturating linear probability.

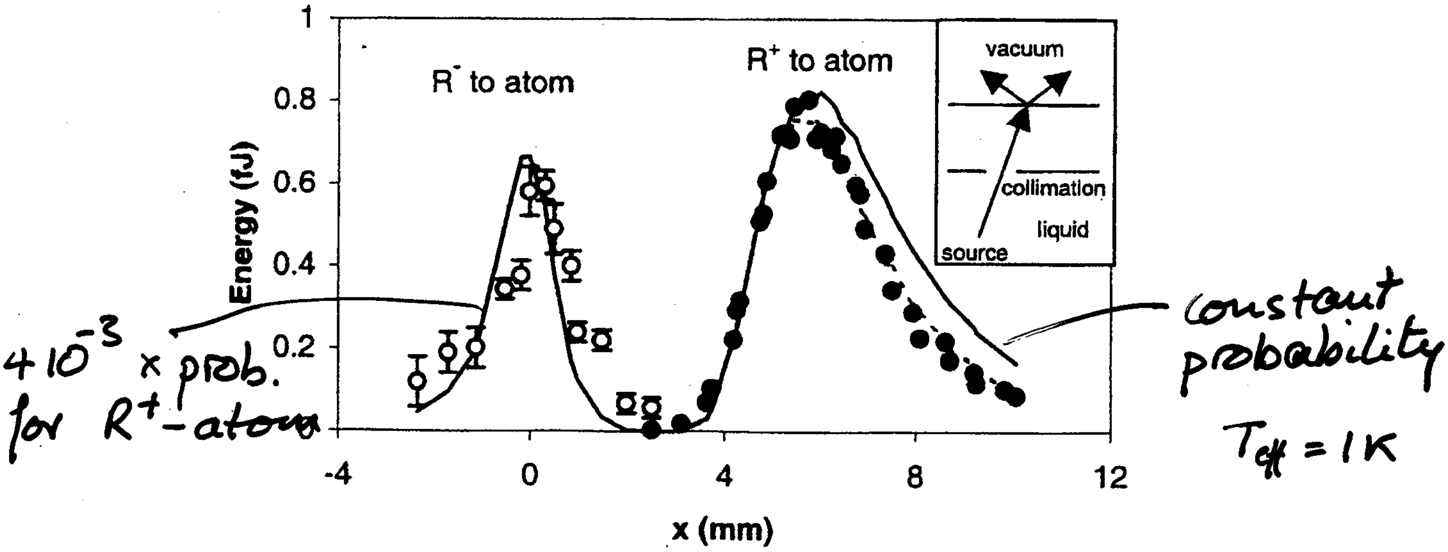


Fig. 1. Evaporation signal as a function of the horizontal position x of the bolometer, where $x = 0$ is the centre of the opening at the top of the cavity. The open circles are plotted at energies 20× larger than actual. The curves are the results of computer simulations with $T_{eff} = 1K$: solid line, $P_{Ra} = constant$; dashed curve, P_{+a} has the linear dependence, saturating at 9.5K, shown in Fig. 2. At top right is a schematic of the geometry.

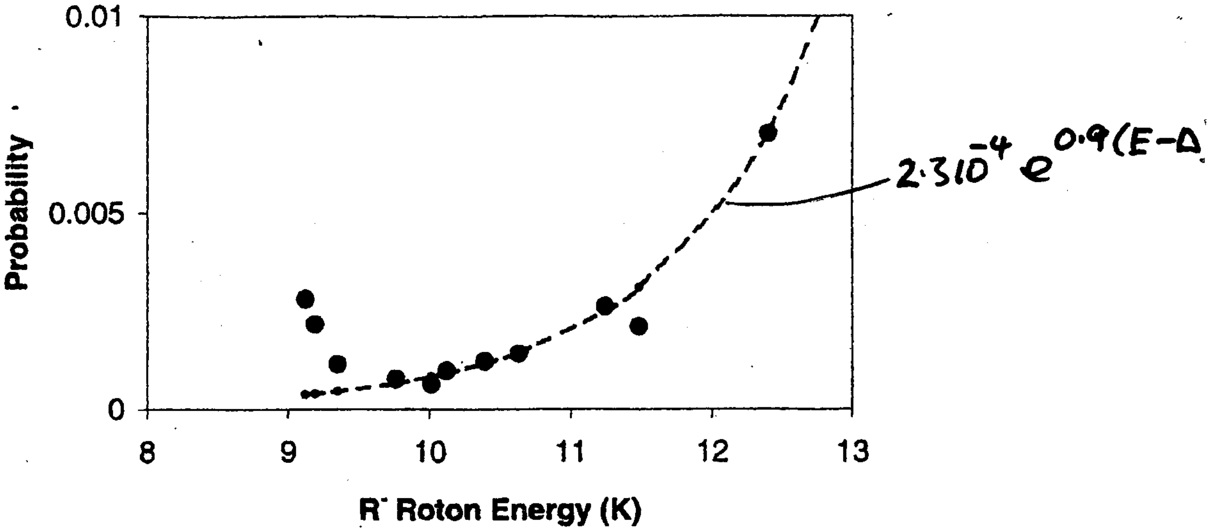


Fig. 3. Evaporation probability for R^- rotons as a function of roton energy. The vertical scale is set by the vertical scale in Fig. 2. The dashed curve is $2.3 \times 10^{-4} exp[0.9(E - \Delta)]$, where E is the roton energy and $\Delta = 8.6K$.

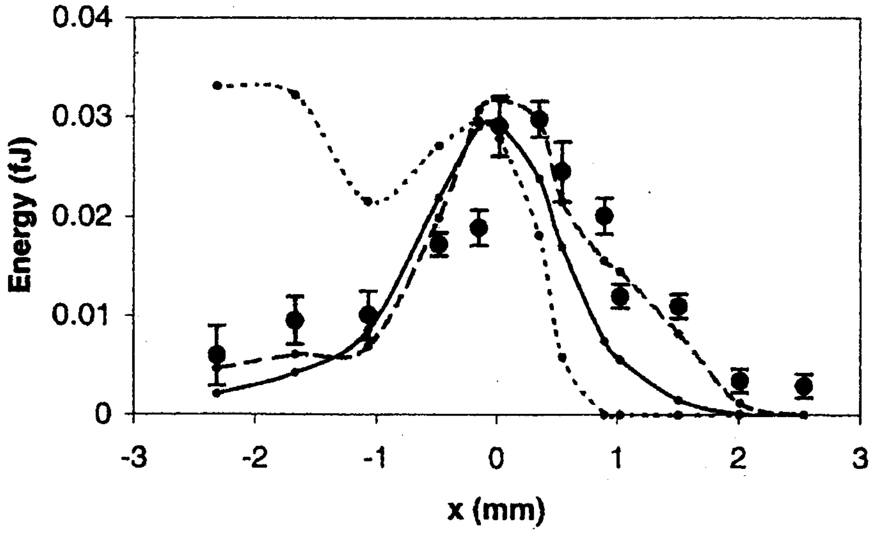


Fig. 4. Atom flux from R^- rotons versus bolometer position x: solid curve, $P_{-a} = constant$; dotted, $P_{-a} = constant$ if $\theta > \theta_C$ but $P_{-a} = 0$ if $\theta < \theta_C$; dashed, $P_{-a} = 3 \times 10^{-3} exp[0.9(E - \Delta)]$ for $\theta > \theta_C$ and $P_{-a}(\theta < \theta_C) = 0.05 \times P_{-a}(\theta > \theta_C)$.

$\theta < \theta_c$ mode-change channel is allowed: $R^- \rightarrow$ phono

this does not forbid $R^- \rightarrow$ atom

as has been suggested.