Acoustic and heat wave measurements across a phase transition in solid ^{4}He

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February 7, 2006

Measurements of propagation of acoustic waves, heat waves, and the interaction of the two

Work reported in 3 papers during the past 15 years:

G. Lengua and J. M. Goodkind, J. Low Temp. Phys. **79**, 251 (1990).

P.-C. Ho, I. P. Bindloss, and J. M. Goodkind, J. Low Temp. Phys. **109**, 409 (1997).

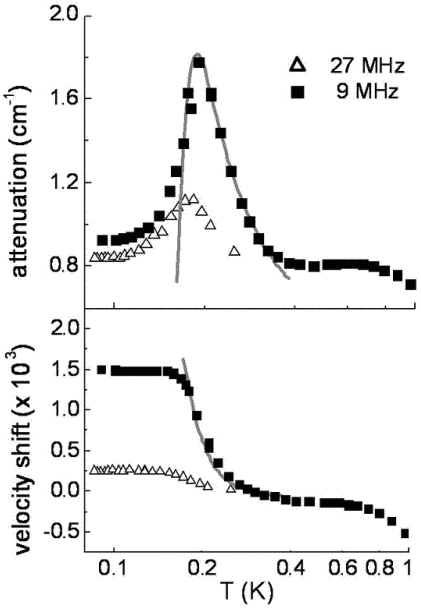
J. M. Goodkind, Phys. Rev. Lett., **89**, 095301 (2002)

The first paper yielded information about the elementary excitations of the system.
The second paper found an acoustic anomaly with the addition of a few ppm of ^{3}He that we interpreted as a continuous phase transition.
The last experiment confirmed the existence of propagating waves not carreid by phonons.

Funding was discontinued after the discovery of the phase transition. Thanks to Moses' discovery these measurements have been given new life.

The acoustic anomaly

Crystal XG2, 27.5 ppm 3He, Grown at 0.86 K (20.983 cc/mole)



Signal is smaller at higher acoustic power levels (saturation?) and therefore at higher frequencies.

The relaxation model:

$$v - v_0 = (v_\infty - v_0)\frac{(\omega\tau)^2}{1+(\omega\tau)^2}$$

$$\alpha = \frac{(v_\infty - v_0)}{v_\infty v_0}\frac{\omega^2\tau}{1+(\omega\tau)^2}$$

$$\tau = \frac{\tau_0}{T - T_C}$$

$\tau_0 = 5.2\text{x}10^{-10}$

$T_C = 0.158$ K

Magnitude and offset also adjustable parameters

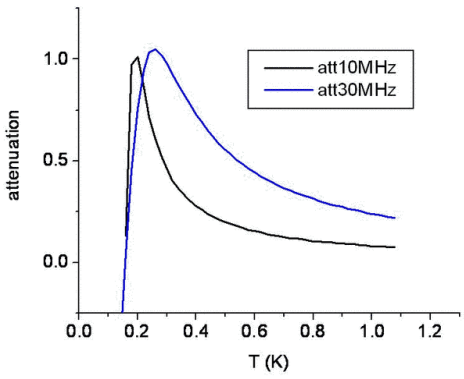
Where might the model disagree with the data?

•The frequency dependence of the T_{peak} and of T_C is very small, as expected but appears to be in the wrong direction. (due to higher power?)

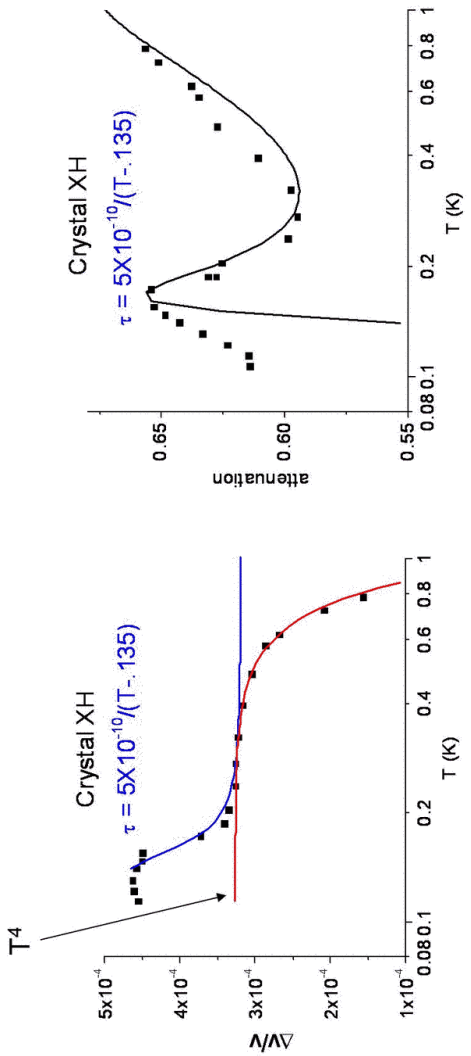
•Signal is more symmetric than the relaxation model. (However, the relaxation time expression should fail very close to T_C)

•$T-T_C$ rather than $T_C - T$?? More discussion of a model later.

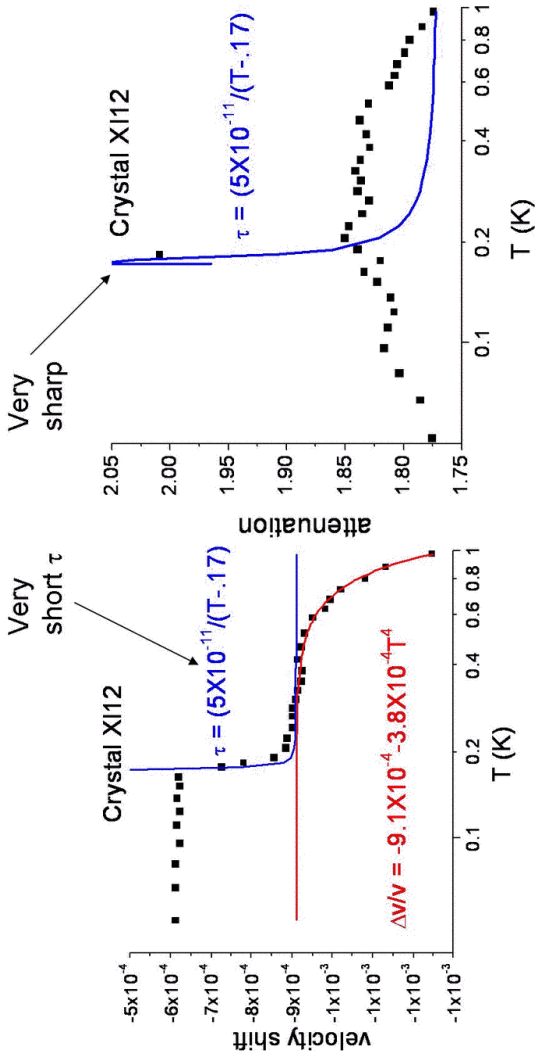
Computed attenuation according to the relaxation model at 10 and 30 MHz



Crystal XH, $\tau_0 = 5X10^{-10}$ and $T_C = .135$ K.
27.5 ppm, $T_{grow} = 0.86$

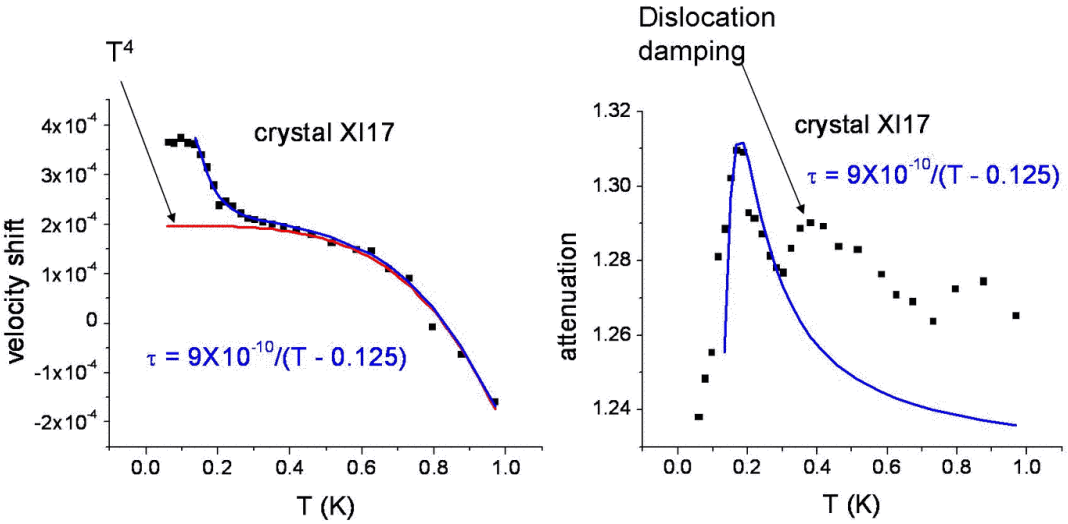


Crystal containing 14 ppm ^{3}He grown at 0.86 K



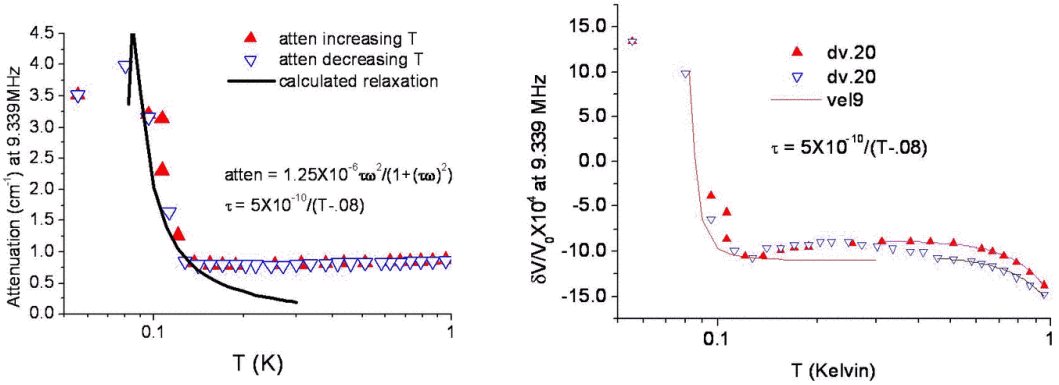
Very sharp transition, $\tau_0 = 5X10^{-11}$ vs $5.2X10^{-10}$ on previous sample

Crystal XI17. ^{3}He concentration 14.7 ppm grown at 0.86 K. Lower dislocation density than previous crystal.



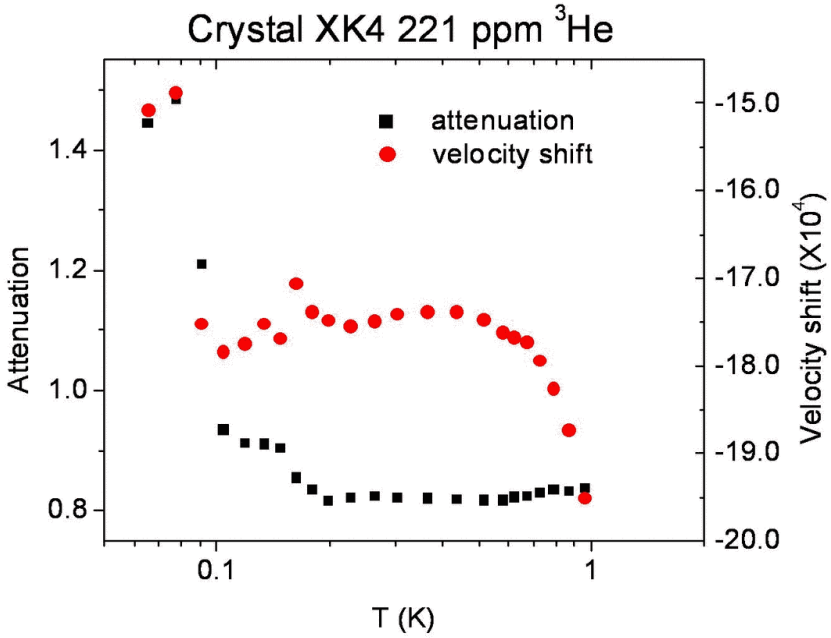
With higher ^{3}He concentration

Crystal XK3 with 221 ppm ^{3}He, grown at 0.86 K



Very large shift in α. T_C is close to extrapolation of phase separation curve so that this could be the phase separation.

There appear to be two anomalies in this crystal. T_C of the one at higher T is consistent with the others, the lower T one is much larger and is close to the extrapolation of the regular solution theory curve for the phase separation.



No anomaly was observed in crystals with 0.3 ppm ^{3}He.

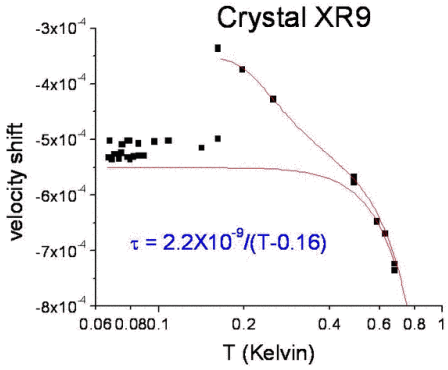
Is there ever an anomaly in pure crystals?

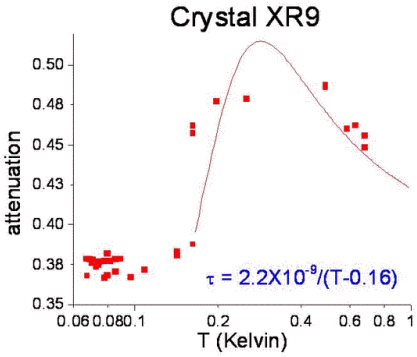
If not is it because:

a) There is no coupling of the acoustic waves to the parameters of the phase change? OR

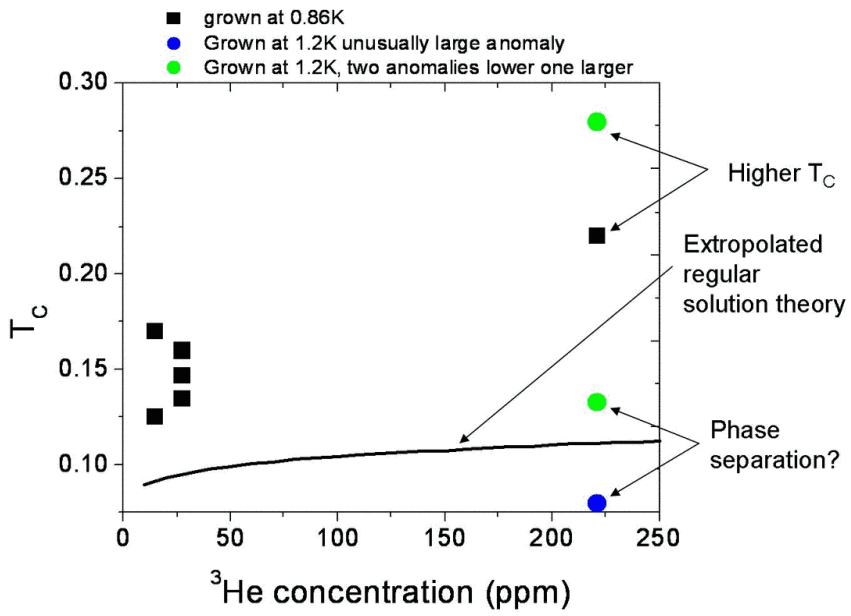
b) There is no phase change in pure solid?

More information about this question from the heat wave experiment, but here is a crystal that was grown with less than 14 ppm. The anomaly is small and spread out (large τ).





T_C vs concentration?



•Two of the data points indicate that T_C increases with ^{3}He concentration.

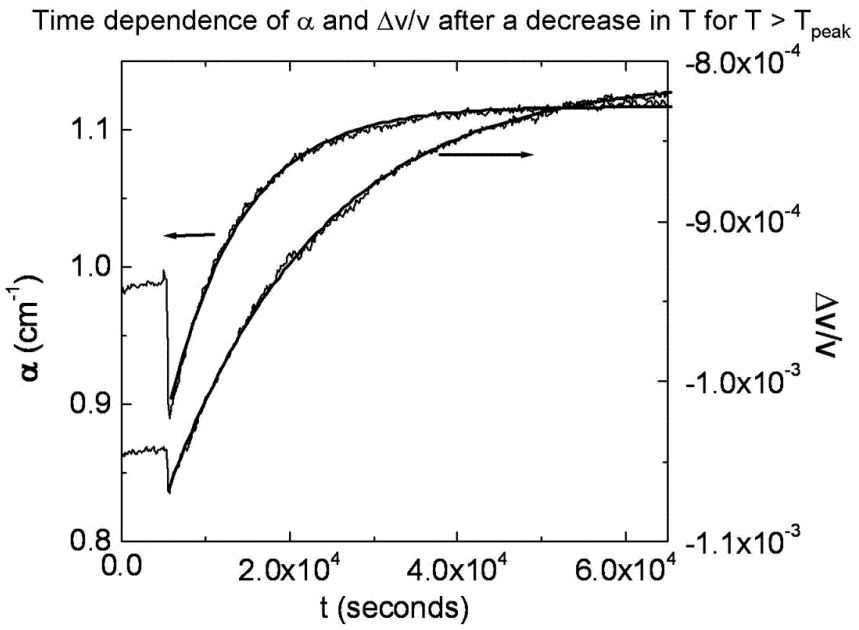
• Within our model this would be consistent with decrease of the concentration of the relevant defectons with increase in ^{3}He.

Summary of properties of various crystals

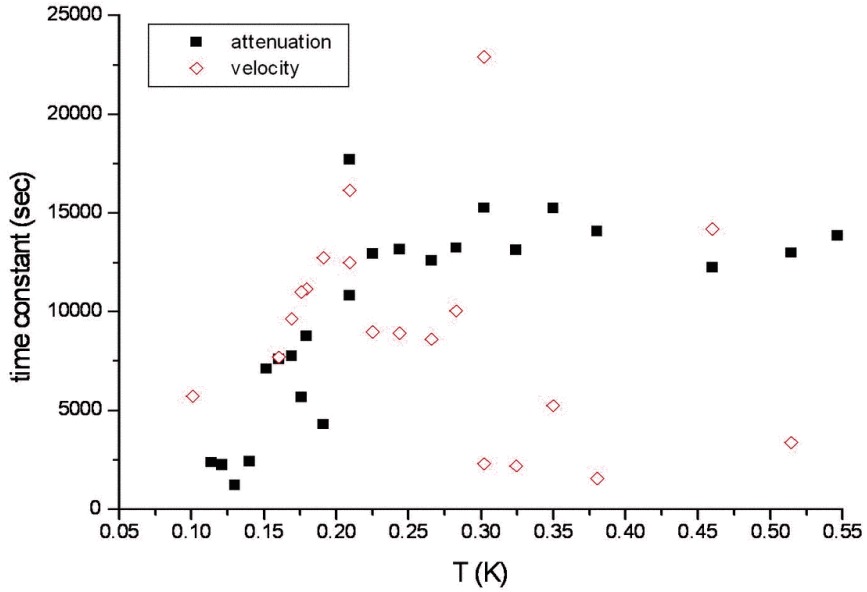
Crystal	T_{grow} (K)	V_{molar}	T_C	τ_0 (sec)	$\Delta v/v$ coeff (9MHz)	T^4 coeff In units of 10^{-4}	$\Delta\alpha$ coeff (9MHz)	Disloc density	^{3}He (ppm)
XG2	0.86	20.983	.147	3.0e-10	1.5e-3	5.5 ±1	4.3e-8		27.5± 0.5
XG2b	0.86	20.983	.16	5.5e-10	1.5e-3	4.7	5e-8		27.5± 0.5
XH	0.86	20.983	.135	5.0e-10				0.1	27.5±0.5
XI12	0.86	20.983	.17	0.5e-10	6e-4	3.8±.09	1.1e-8	0.6	14.5±1.5
XI17	0.86	20.983	~.125	9.0e-10	1.8e-4	4.2	0.3e-8	0.3	14.5±.1.5
XK3	0.86	20.983	.22	25e-10	0.22e-4	5.5	0.1e-9	0.1	221±17
XK4	1.2	20.972	.28	6e-10	1.2e-4	1.5	0.12e-8		221±17
XK4lowT	1.2	20.972	.133	1.5e-10	1.2e-4	1.5	0.12e-8		221±17
XR9			.16	22.0e-10	1.5e-4	9.5	0.46e-8	--	

Another puzzling property

Three very different time constants in the system.



Long time constant vs T



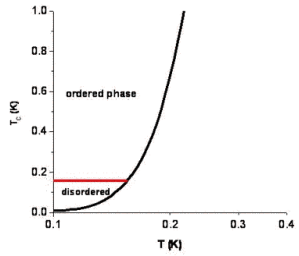
Evidence for very long lived excitations.

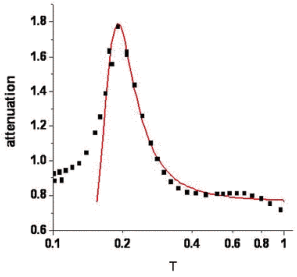
A model

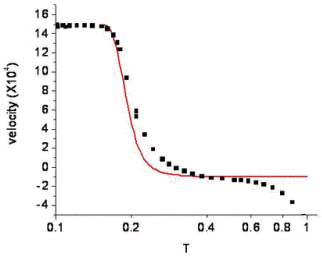
An ordered phase of the thermal excitations. T_C decreases with decreasing T proportional to defecton density. For example:

a) Bose condensation of long lived excitations?

b) Spatial ordering of excitations when their density is high?







$$\tau = \frac{\tau_0}{T_C(T) - T}$$

$$T_C(T) = T_0 e^{-\phi/T}$$

Short time constant is time to change T of existing defecton population.

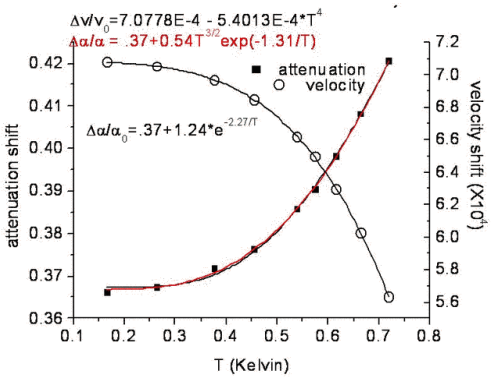
Long time constant is time to change density of defectons.

Ordered phase is below T_C as usual.

This implies that there is an order parameter at high T which goes to zero at low T. Would violate thermodynamics if the total order in the system decreased upon cooling (would imply negative specific heat).

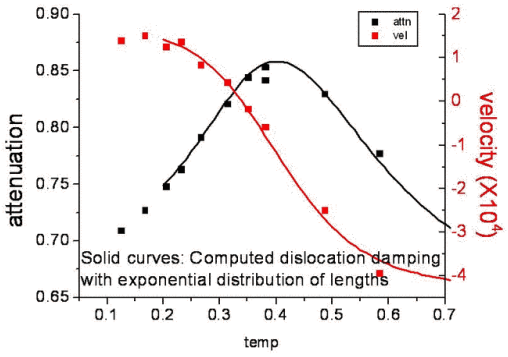
There would need to be some compensating decrease in entropy (e.g. momentum order replacing spatial order)

Other properties



Cyrstal XT3 *Low* dislocation density

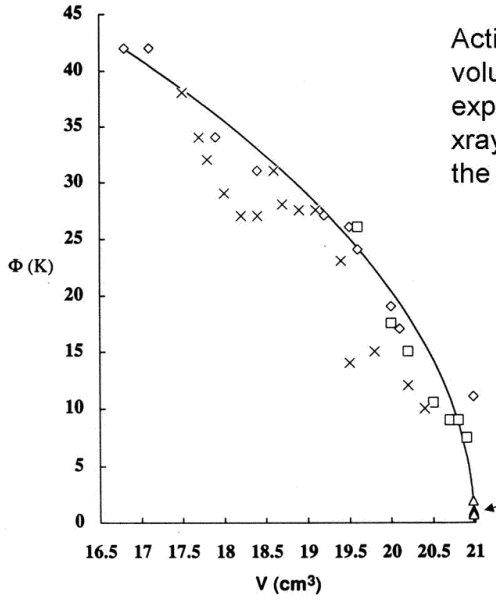
Attenuation due to thermally activated excitations with Δ ~ 1 K. Velocity shift is due to anharmonic phonons. Nature of the "defectons" not known.



Cyrstal XT5, *High* dislocation density

Attenuation and velocity due to dislocation damping phenomenon fit by classical theory.

These "defectons" could be vacancies



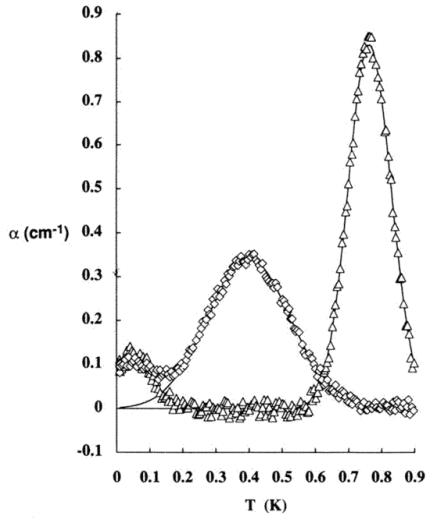
Activation energy as a function of molar volume from a wide range of experiments, including nmr, acoustics, xrays. Solid curve is a fit to our data of the form.

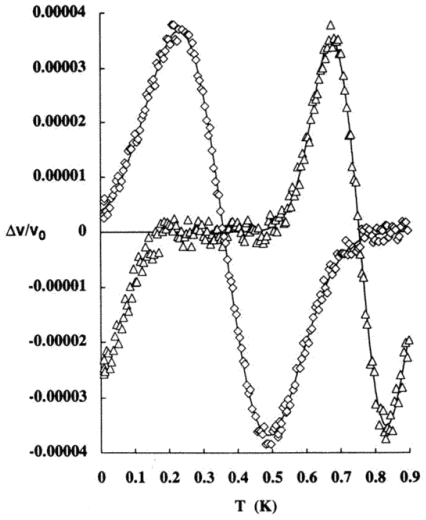
$$\Phi = 5.2\left(T_m - 0.78\right)$$

UCSD data

In very high quality , high purity, crystals, subtract the exponential and T^4 dependences, measured at 10 MHz from the data mesured at 30 and 50 MHz. Find resonant response.

Mode coupled to acoustic waves with T dependent velocity.

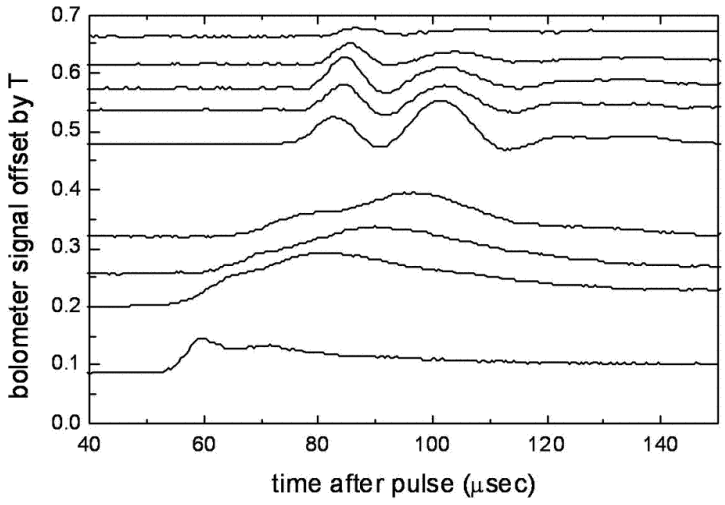




•Growth technique for exceptionally perfect crystals dislocation density < 200/cm.

•Measurement of ^{3}He concentration before and after experiment. (no *in situ* measurements. Is there zone refining during crystal growth?)

Heat pulse propagation



Diffusive flow at Highest T , then second sound (reflections from side walls), then "ballistic" regime.

However, the "ballistic" signal is too large for the slow transverse phonon mode.

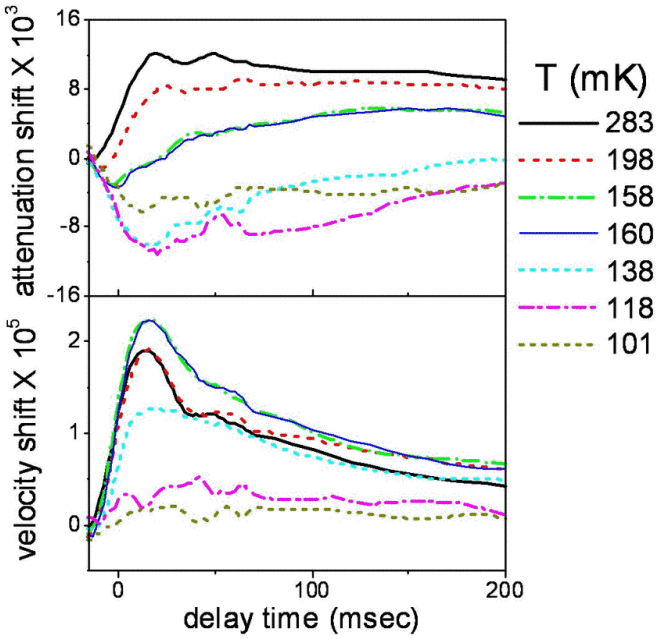
Interaction of heat waves and acoustic waves

Evidence for the transition in pure solid, if strained.

Evidence for an energy gap in the excitation of the traveling waves at T below the 2nd sound regime.

Confirms presence of traveling wave generated by the heat pulse that interacts with acoustic wave but is not detected by the bolometer.

Response to collision of acoustic wave with heat wave is necessarily rapid and is always opposite to equilibrium T dependence. As in the previous experiment where T changes were created by hand.



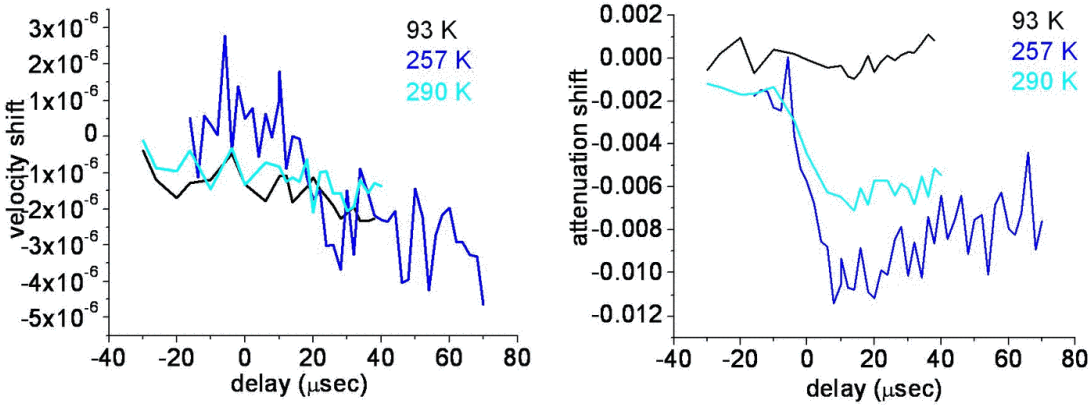
No interaction is observed in pure, unstrained crystals.

But in this crystal, strained by rapid heat change:

Shift is small and always opposite to equilibrium T dependence

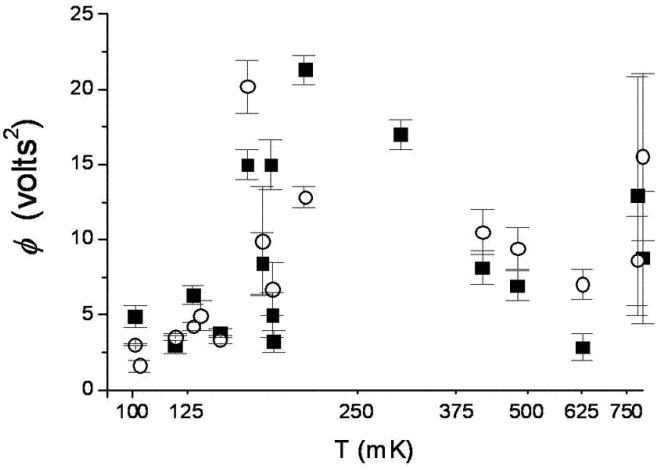
Same as behavior below T_P for impure crystals.

Consistent with a very broad transition (very large τ)



The amplitude of the shift in acoustic properties, above T_C, increases exponentially with the power in the heat pulse ($exp(V^2)$). Below T_C the amplitude increases proportional to V^2.

Energy gap vs T



How is this related to the other measured properties??

Summary of properties measured or inferred

In high quality, pure crystals

•Family of excitations with low activation energy ($\alpha = \alpha_0 \exp(-\Phi/T)$, $\Phi \cong 1$ K, data shown above)

•Lattice anharmonicity ($\Delta v/v = v_0(1-bT^4)$, $b \cong 5X10^{-4}$

• A non-phonon propagating mode with T dependent velocity (resonance in $\Delta v/v$ and α as a function of T. Other possible explanations?)

In impure or strained crystals

•Acoustic anomaly indicates a phase transition

•Three time constants of the system. Long one indicates long lived defectons

•Heat pulse propagates a wave that interacts weakly with the bolometer (infer that it is carried by the long lived defectons)

•Pure crystals display the effects of the transition only if strained.

•Energy gap above T_C