PSI Center for Neutron and Muon Sciences

University of Zurich UZH

# Resonant Ultrasound Spectroscopy (RUS) A Study of the Vortex Lattice Phase Diagram of Niobium

## Swiss Physical Society meeting 2024

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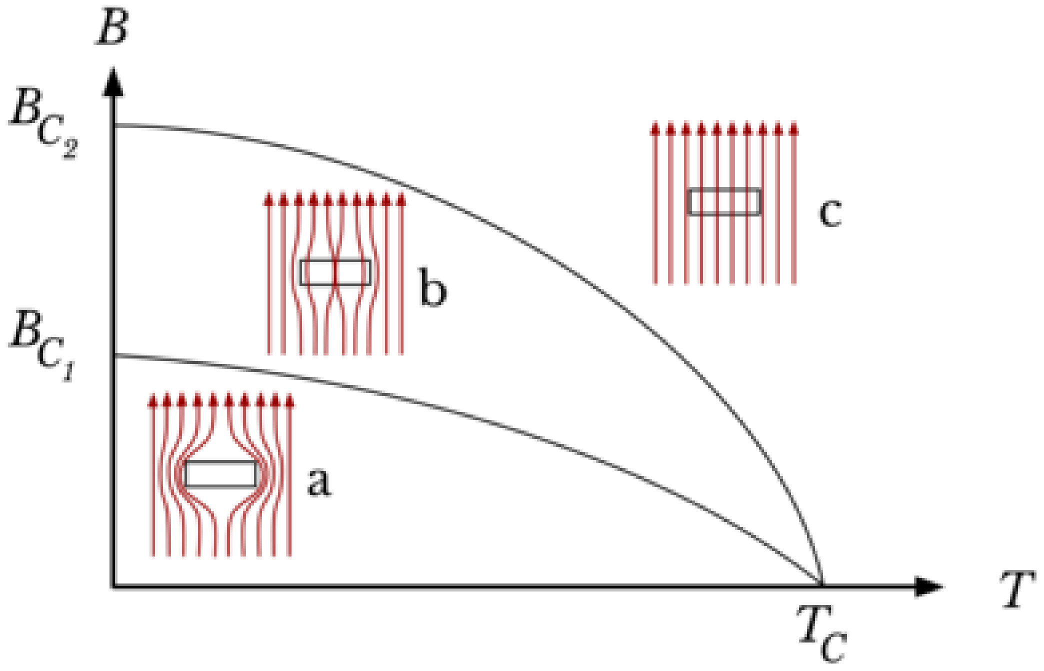
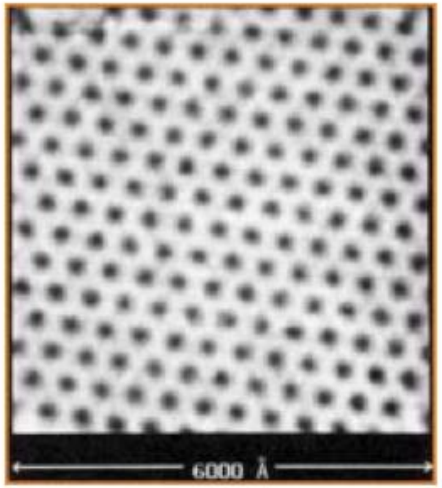
# Vortex Matter in Superconductors




**Type II superconductor**

- $\kappa > 1/\sqrt{2}$
- External magnetic field allows passing via quantised vortex lines

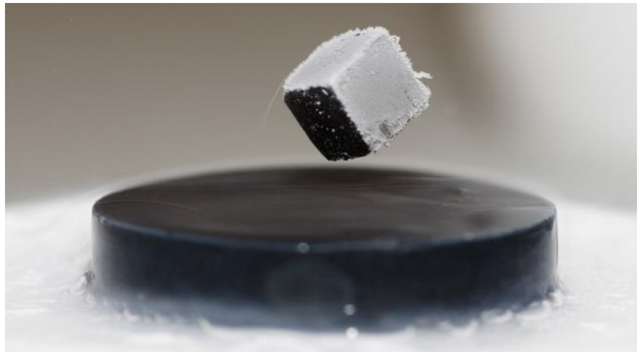
Repulsive interaction between vortices.



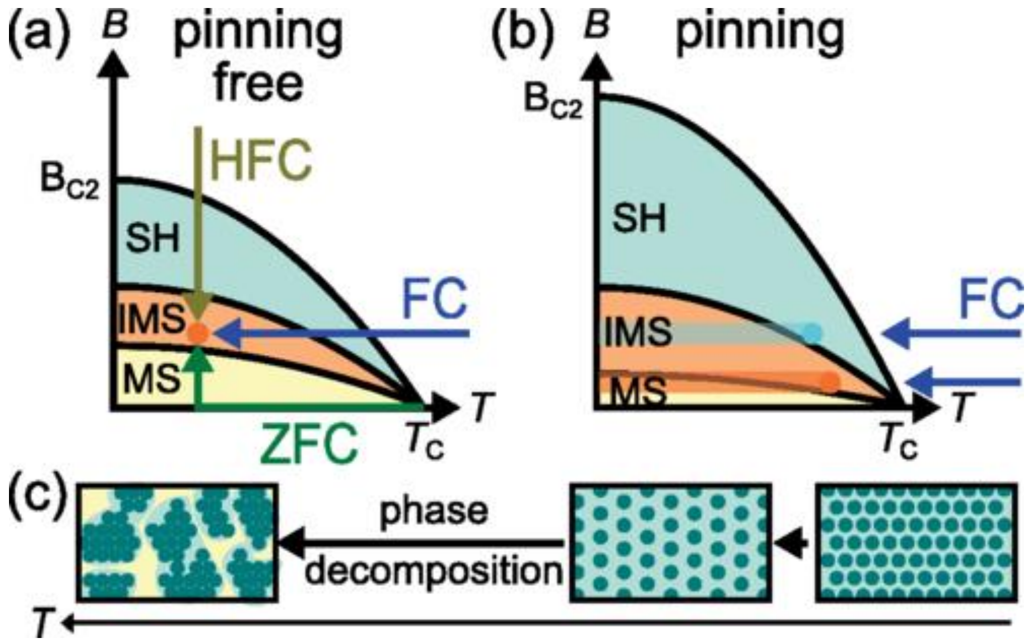

*Scanning Tunnel Microscopy NbSe2, 1T, 1.8K*

*H. F. Hess et al., Bell Labs*

Pinning of vortex lines.



# Vortex Matter in Niobium




T. Reimann et al Physical Review B 96, 144506 (2017)

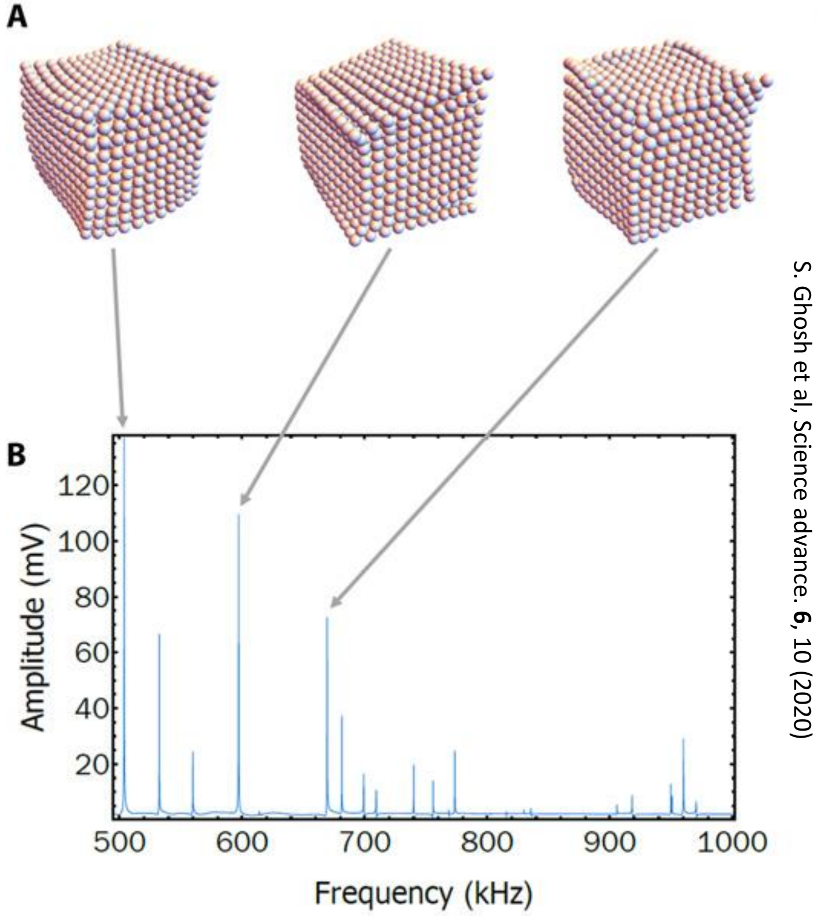
**Type II Superconductor**

- Superconducting Transition Temperature 9.2K
- $B_{c2}$ ~ 0.5T

**Vortex matter in Niobium**

- Immediate Mixed phase 0.1T < B < 0.2T
- Shubnikov phase

# Resonant Ultrasound Spectroscopy (RUS) and Elasticity of Crystals




S. Ghosh et al, Science advance. **6**, 10 (2020)

- RUS measures Eigenmodes of the sample
- Depend on sample dimensions, density and elastic modulus
- RUS measures all elastic moduli $c_{ij}$ simultaneously.
- RUS is highly sensitive to changes in lattice strength.

**For example:**
BCC crystal has 3 components to the elastic tensor

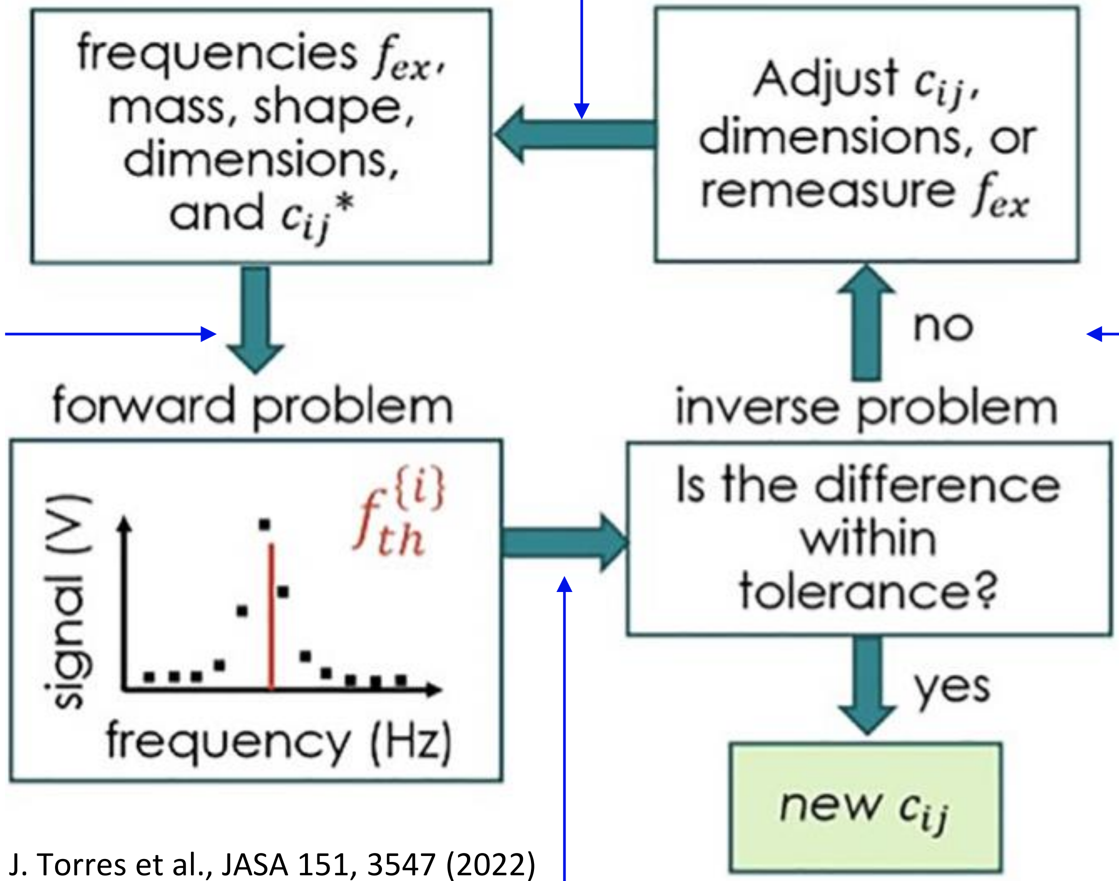
$$\begin{pmatrix} c_{11} & c_{12} & c_{12} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{12} & 0 & 0 & 0 \\ c_{12} & c_{12} & c_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{44} \end{pmatrix}$$

$c_{11}$ .. compression
$c_{12}$ .. torsion
$c_{44}$ .. shear

# Spectrum computation

Adapt input parameters

Calculate Eigen frequencies by Rayleigh-Ritz method.




Get the new initial $c_{ij}^{*}$

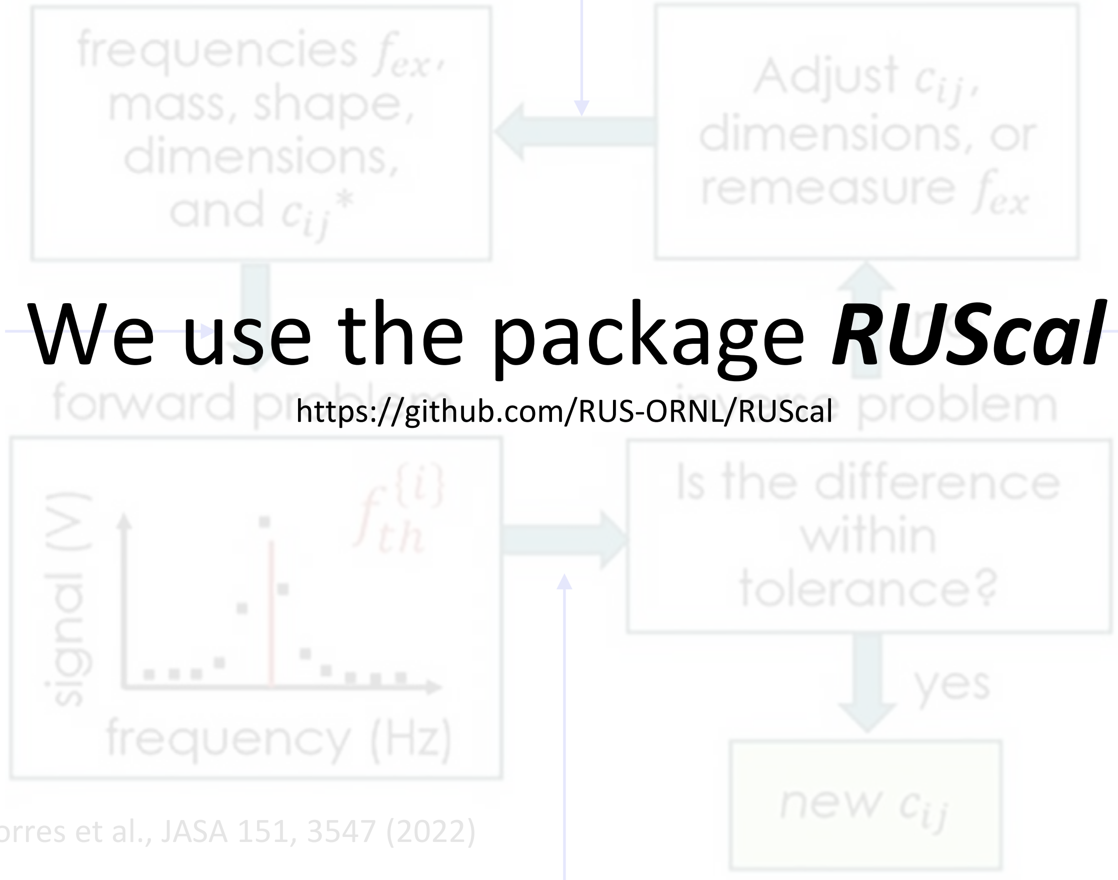
J. Torres et al., JASA 151, 3547 (2022)

Compare calculation to experiment

# Spectrum computation

Adapt input parameters

Calculate Eigen frequencies by Rayleigh-Ritz method.




Get the new initial $c_{ij}^*$

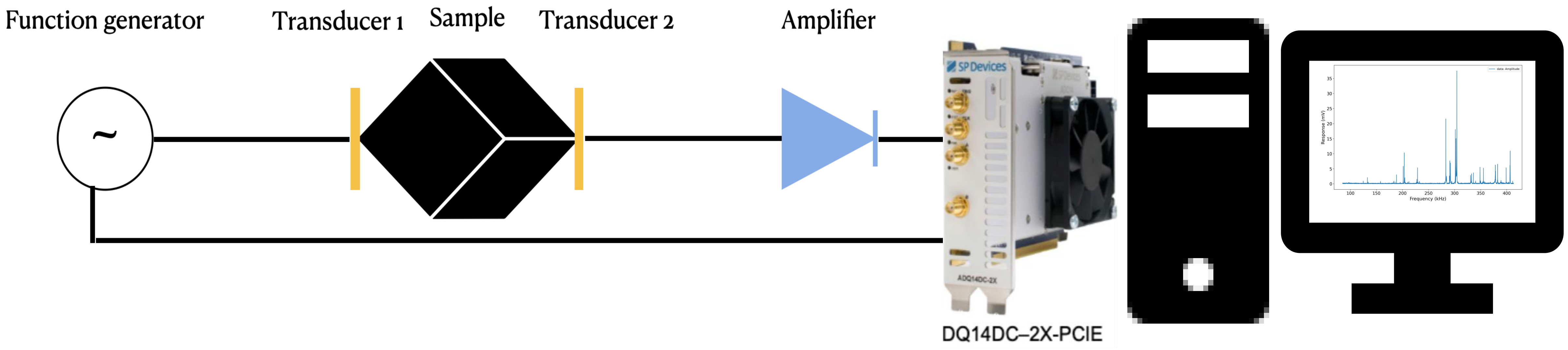
# We use the package ***RUScal***

https://github.com/RUS-ORNL/RUScal

J. Torres et al., JASA 151, 3547 (2022)

Compare calculation to experiment

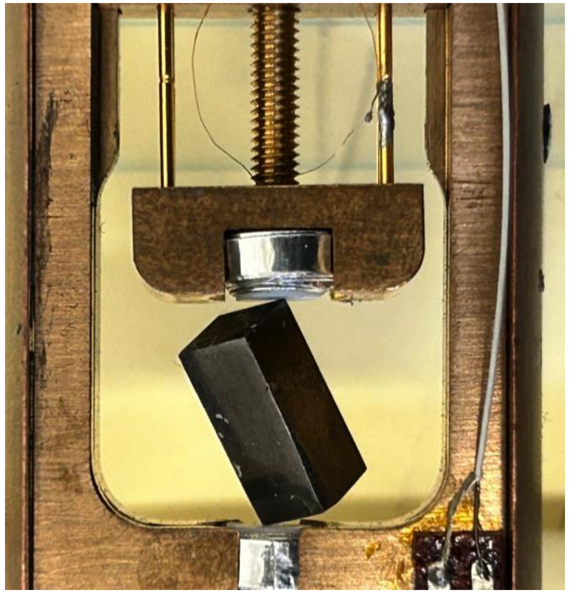
# RUS experimental setup



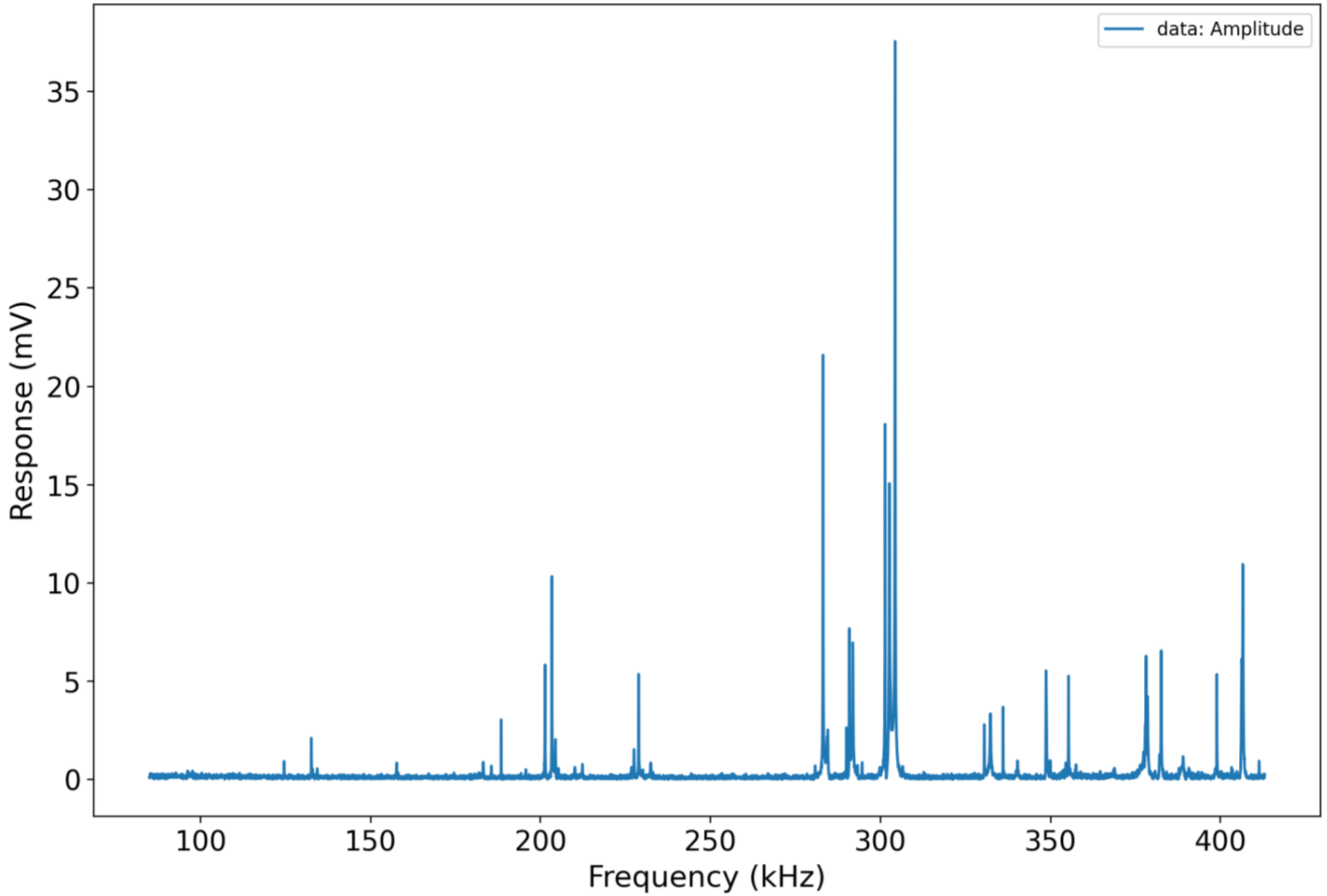

- Crystal is clampled by transmitter and receiver transducers.
- F.G controls the frequency of excitation.
- Amplifier gain the response signal.
- DAQ records data and plotting in screen of PC.

# RUS Spectrum of Niobium (Nb)

PSI



**Nb crystal in stick**

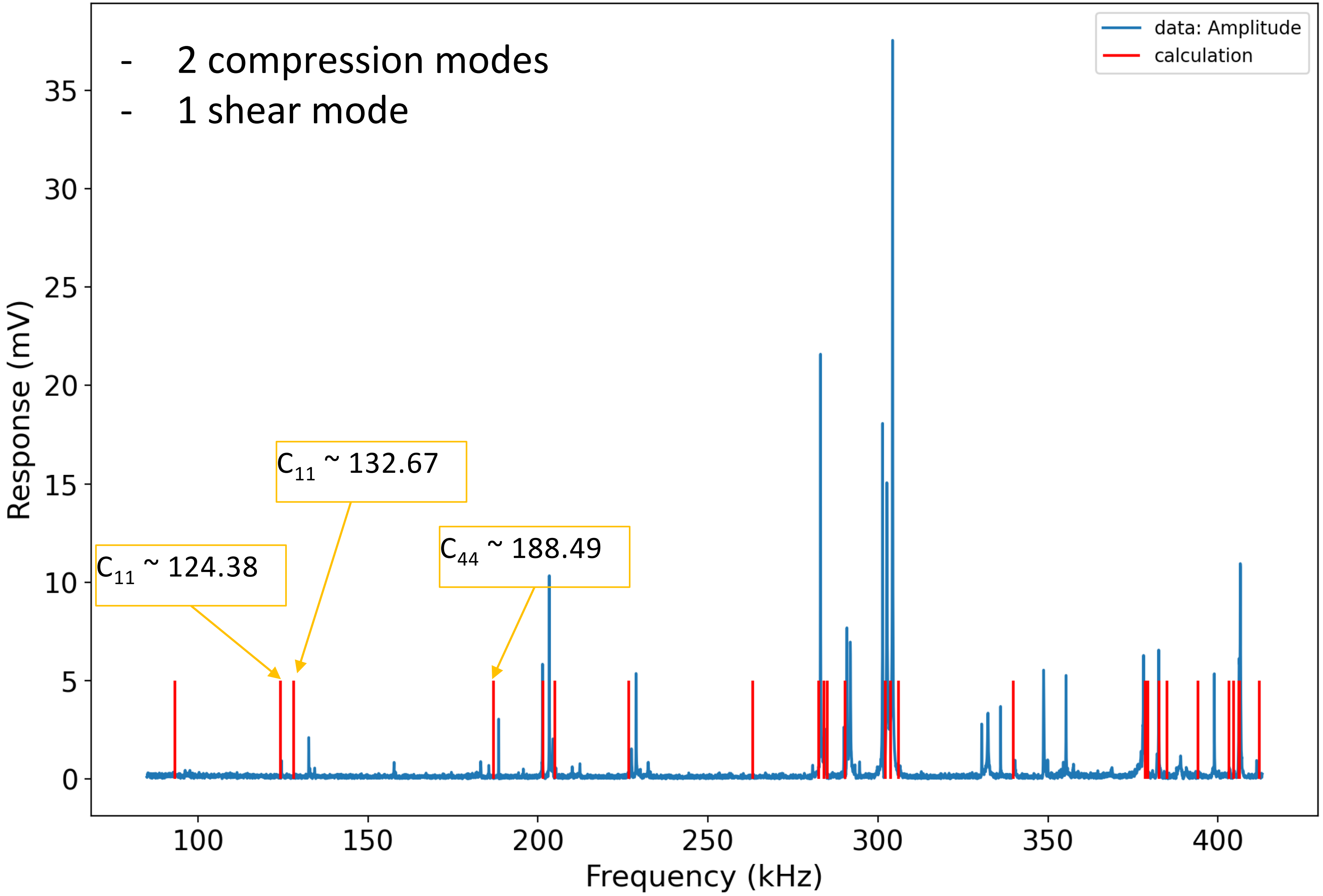



**RUS spectrum of Nb at  T = 16K**

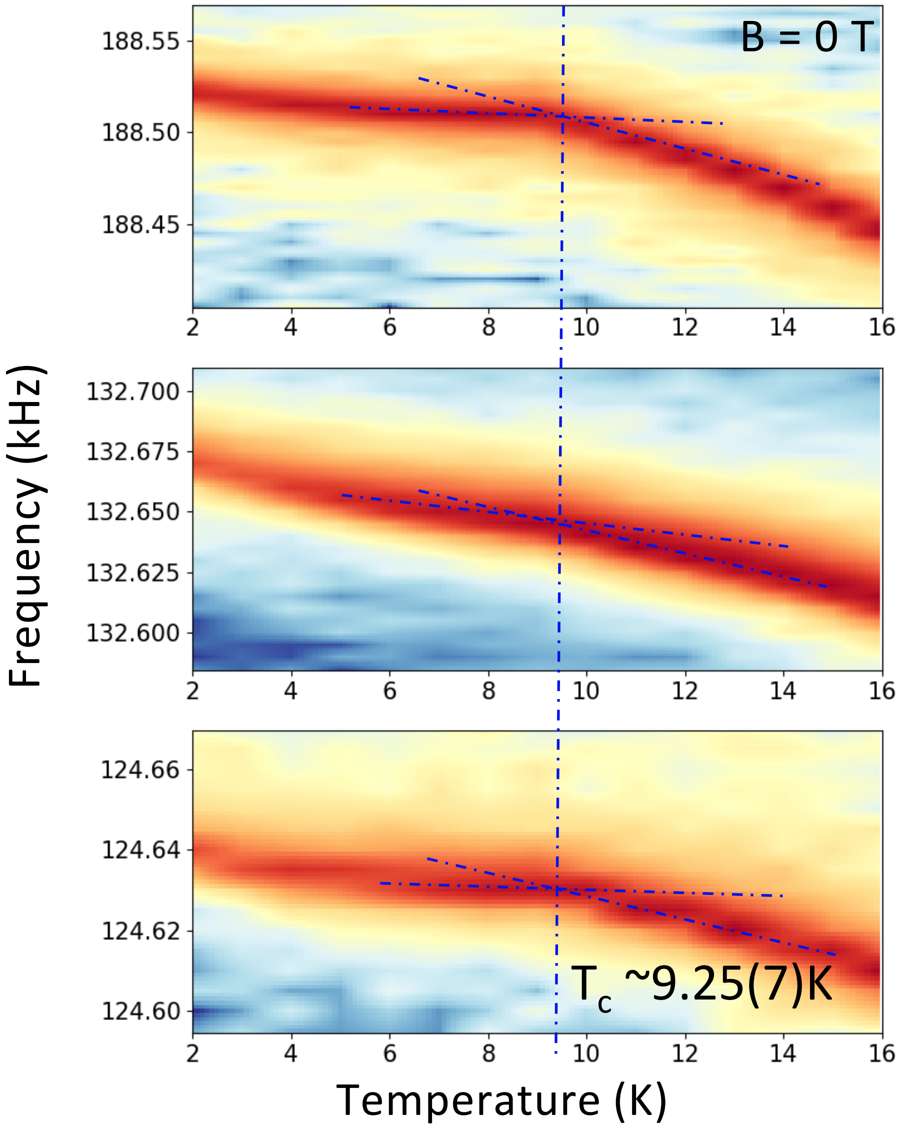
- Rectangular shape.
- Dimensional: 3.84 x 4.10 x 9.40 $mm^3$
- Mass: 1.2528 g
- $c_{11}$ = 245.6 GPa, $c_{12}$ = 138.7 GPa, $c_{44}$ = 29.3 GPa (*)

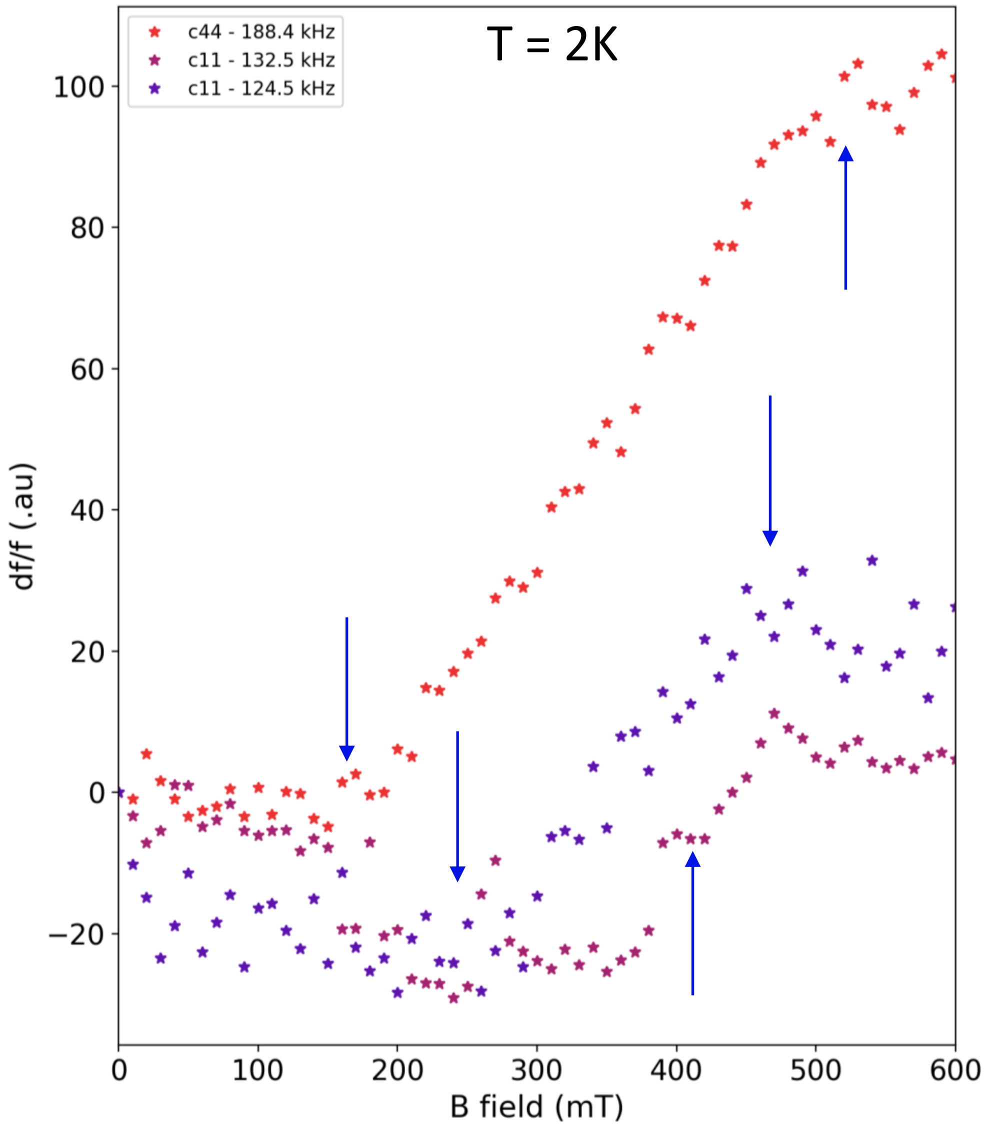
(*): *By K. J. Carroll thesis, 1962*

# Comparison measured and calculated Spectrum

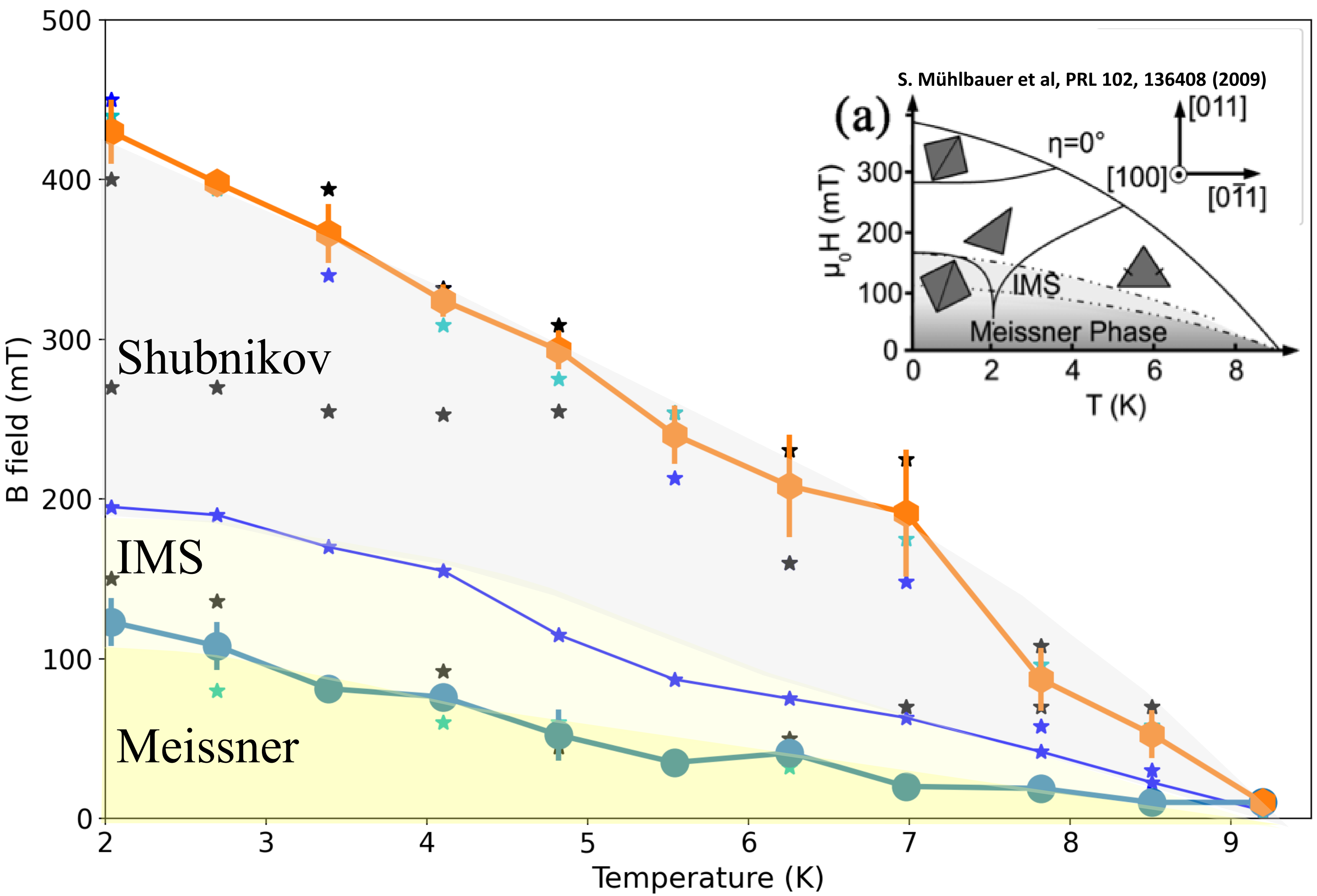


# Eigenmodes as function of tuning parameters



# Phase transition of Niobium by RUS measurement.



# Conclusion

Developed RUS experiment successful investigate the phase transition of Niobium cause the change of elasticity.

RUS useful tool for the investigation vortex phases and phase transitions

# Acknowledgments

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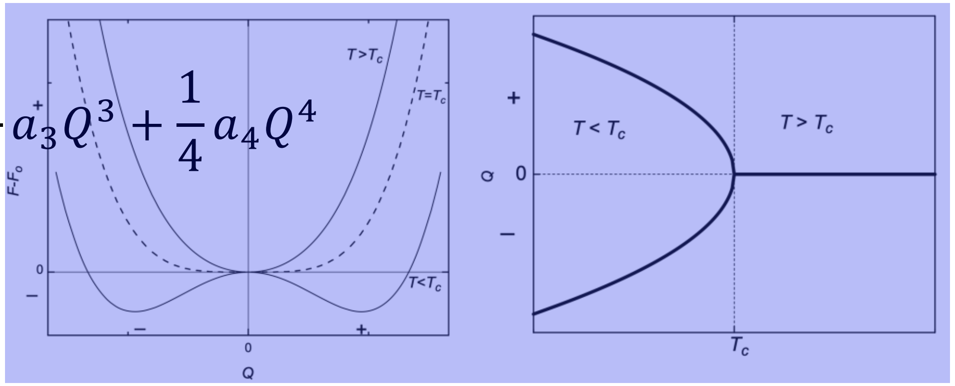
# Supplementary Information

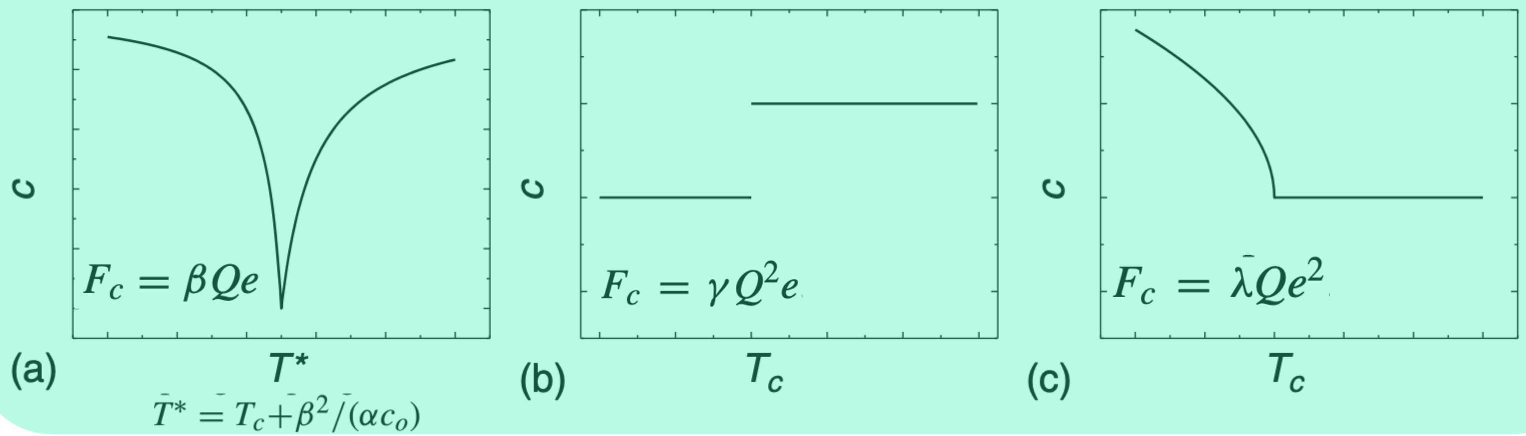
In the second-order phase transition, Landau theory:

$$F(Q,T) = F_0(T) \quad + \ a_1 Q + \frac{1}{2} a_2 Q^2 + \frac{1}{3} a_3 Q^3 + \frac{1}{4} a_4 Q^4$$

$$+ F_c + \frac{1}{2} c_0 e^2$$

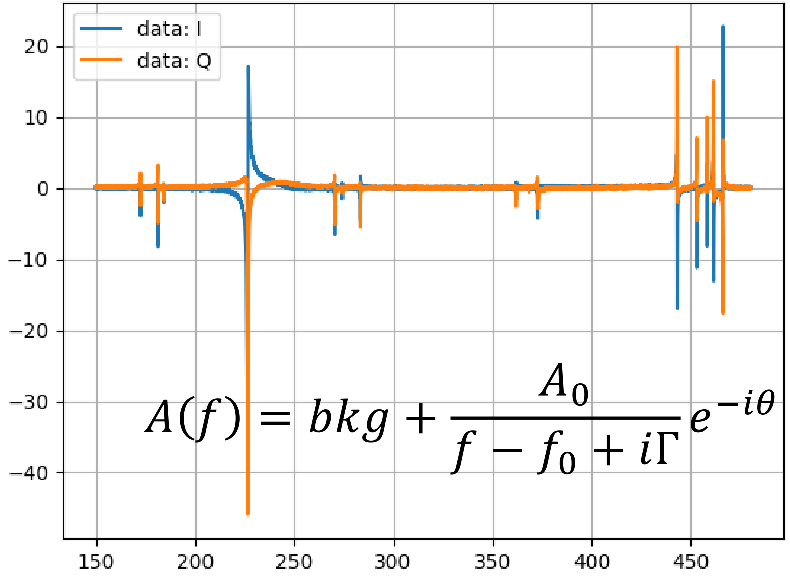



Adding the term for order parameter (Q) and elastic strain (e) coupling ($F_c$) and elastic energy



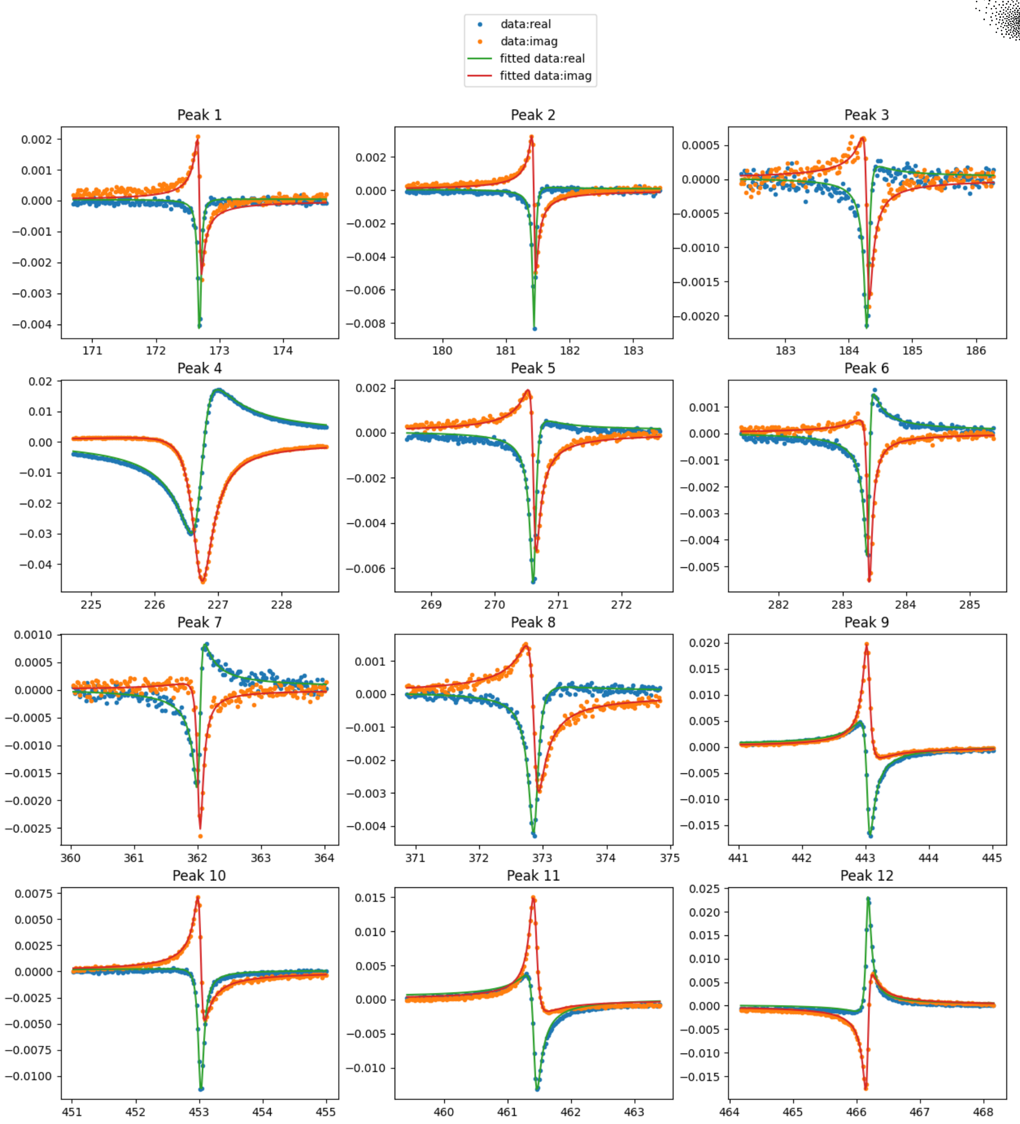

Robert G. Leisure et al. *Ultrasonic spectroscopy*. chapter 5

# Supplementary Information




$$A(f) = bkg + \frac{A_0}{f - f_0 + i\Gamma} e^{-i\theta}$$

| | a | f0 | gamma | psi | bkg | ampl |
|---|---|---|---|---|---|---|
| 0 | 0.138932 | 172688.774584 | 31.568018 | -1.486012 | 0.000039 | 0.006952 |
| 1 | 0.243688 | 181442.693651 | 29.099660 | -1.359570 | 0.000063 | 0.013217 |
| 2 | 0.114655 | 184296.355237 | 48.180994 | -1.056724 | 0.000028 | 0.003766 |
| 3 | 9.189233 | 226718.308593 | 195.685216 | -0.336902 | 0.001378 | 0.075141 |
| 4 | 0.407319 | 270620.070202 | 56.616396 | -1.081214 | 0.000086 | 0.011387 |
| 5 | 0.270674 | 283413.107904 | 43.745395 | -0.573973 | 0.000063 | 0.009782 |
| 6 | 0.144141 | 362026.436337 | 54.879735 | -0.406547 | 0.000034 | 0.004160 |
| 7 | 0.408352 | 372867.927439 | 92.077797 | -1.224203 | 0.000076 | 0.007042 |
| 8 | 1.397320 | 443042.657529 | 64.441224 | -2.511157 | 0.000286 | 0.034347 |
| 9 | 0.626876 | 453024.626812 | 53.159098 | -1.776801 | 0.000133 | 0.018657 |
| 10 | 1.163777 | 461432.159021 | 69.262600 | -2.487403 | 0.000238 | 0.026631 |
| 11 | 1.127121 | 466174.870531 | 45.675569 | 1.085989 | 0.000263 | 0.039025 |



# Elastic tensor computing

| n | fexp(MHz) | fcalc(MHz) | %err | wt | dlnf/dlnc11 | dlnf/dlnc12 | dlnf/dlnc44 | sum |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.0966910 | 0.0936072 | -3.19 | 0.00 | 0.01058 | -0.00545 | 0.99460 | 0.99974 |
| 2 | 0.1243830 | 0.1238165 | -0.46 | [illegible] | 1.29546 | -0.64098 | 0.34314 | 0.99762 |
| 3 | 0.1326780 | 0.1276039 | -3.82 | [illegible] | 1.25959 | -0.62301 | 0.36101 | 0.99759 |
| 4 | 0.1884900 | 0.1877040 | -0.42 | 1.00 | 0.04728 | -0.02415 | 0.97655 | 0.99968 |
| 5 | 0.2013840 | 0.2016217 | 0.12 | 1.00 | 0.38046 | -0.18681 | 0.80493 | 0.99858 |
| 6 | 0.2045440 | 0.2049890 | 0.22 | 1.00 | 0.47008 | -0.23143 | 0.75972 | 0.99837 |
| 7 | 0.2268960 | 0.2247837 | -0.93 | 1.00 | 2.02363 | -1.02535 | 0.00003 | 0.99832 |
| 8 | 0.2808700 | 0.2642724 | -5.91 | 1.00 | 0.11519 | -0.06003 | 0.94423 | 0.99939 |
| 9 | 0.2831800 | 0.2849427 | 0.62 | 1.00 | 0.25013 | -0.12331 | 0.87235 | 0.99917 |
| 10 | 0.2845050 | 0.2852637 | 0.27 | 1.00 | 0.58337 | -0.29020 | 0.70588 | 0.99905 |
| 11 | 0.2846990 | 0.2860489 | 0.47 | 1.00 | 0.09084 | -0.04699 | 0.95574 | 0.99958 |
| 12 | 0.2909300 | 0.2912385 | 0.11 | 1.00 | 0.20617 | -0.10177 | 0.89490 | 0.99930 |
| 13 | 0.3028560 | 0.3025830 | -0.09 | 1.00 | 0.80270 | -0.40820 | 0.60459 | 0.99910 |
| 14 | 0.3044030 | 0.3041980 | -0.07 | 1.00 | 0.79020 | -0.40455 | 0.61326 | 0.99892 |
| 15 | 0.3068540 | 0.3069968 | 0.05 | 1.00 | 0.04265 | -0.01419 | 0.97126 | 0.99972 |
| 16 | 0.3406100 | 0.3410209 | 0.12 | 1.00 | 0.20467 | -0.08898 | 0.88340 | 0.99909 |
| 17 | 0.3808760 | 0.3811810 | 0.08 | 1.00 | 0.58716 | -0.26817 | 0.67908 | 0.99807 |
| 18 | 0.3823940 | 0.3821377 | -0.07 | 1.00 | 0.86308 | -0.43581 | 0.57010 | 0.99738 |
| 19 | 0.3827420 | 0.3841636 | 0.37 | 1.00 | 0.14384 | -0.07397 | 0.92952 | 0.99939 |
| 20 | 0.3893330 | 0.3893532 | 0.01 | 1.00 | 0.42145 | -0.21570 | 0.79335 | 0.99909 |
| 21 | 0.3908650 | 0.3965475 | 1.45 | 1.00 | 0.55082 | -0.27360 | 0.72143 | 0.99864 |
| 22 | 0.3989490 | 0.4019516 | 0.75 | 1.00 | 1.18078 | -0.62251 | 0.43689 | 0.99516 |
| 23 | 0.4036940 | 0.4021275 | -0.39 | 1.00 | 1.60025 | -0.84621 | 0.24342 | 0.99747 |
| 24 | 0.4064160 | 0.4078617 | 0.36 | 1.00 | 0.36414 | -0.17471 | 0.81002 | 0.99945 |
| 25 | 0.4067130 | 0.4084954 | 0.44 | 1.00 | 0.28952 | -0.14000 | 0.84954 | 0.99906 |

| c11 | c22 | c33 | c23 | c13 | c12 | c44 | c55 | c66 |
|---|---|---|---|---|---|---|---|---|
| 250.28 | 250.28 | 250.28 | 133.68 | 133.68 | 133.68 | 31.172 | 31.172 | 31.172 |

| dx(cm) | dy(cm) | dz(cm) |
|---|---|---|
| 0.3840 | 0.4100 | 0.9400 |

Shape set to rectangular parallelepiped.