Signatures of the chiral anomaly in lattice vibrations

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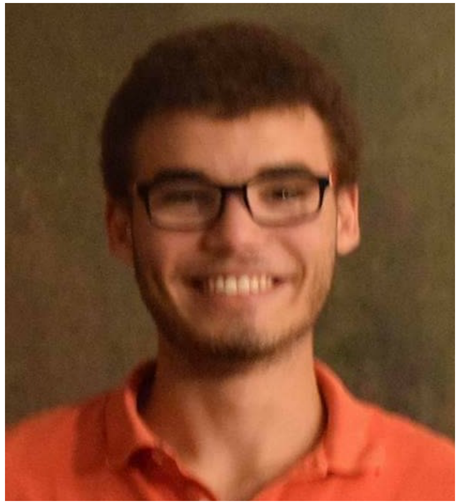

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Outline

1. Motivation
2. Signatures of the chiral anomaly in optical phonons
    - 2. 1) Infrared absorption
    - 2. 2) Hybridization between optical phonons and electronic excitations
3. Signatures of the chiral anomaly in acoustic phonons
    - 3. 1) Sound velocity
    - 3. 2) Phonon magnetochiral effect
4. Conclusions

Motivation: chiral anomaly in Weyl semimetals (WSM)

- Collinear electric and magnetic fields induce a charge transfer between Weyl nodes of opposite chirality.

- Axion term in the electromagnetic Lagrangian:

$$\mathcal{L}_{\mathrm{ax}} = \theta \mathbf{E} \cdot \mathbf{B}\text{, where } \theta = \frac{\alpha}{4\pi^2}\left(\mathbf{b} \cdot \mathbf{r} - b_0 t\right)$$

momentum separation
(needs broken time-reversal)

energy separation
(needs broken inversion and mirrors)

- Leading experimental signature: negative longitudinal magnetoresistance.

  Problem: current jetting → the measured resistivity is not the intrinsic resistivity

  Things may be better with thermal conductivity.

- Nonelectronic probes of the chiral anomaly?

Lattice vibrations

- Equation of motion: driven harmonic oscillator

Phonon frequency

Phonon momentum

Phonon effective charge (vector)

$$(\omega^2 - \omega_{\mathbf{q}}^2) u(\mathbf{q}, \omega) = \mathbf{Q}(\mathbf{q}, \omega) \cdot \mathbf{E}(\mathbf{q}, \omega)$$

Bare phonon frequency

Normal coordinate

Total electric field (external + internal)

- The internal (phonon-induced) electric field approximately parallel to **q**

- What is the influence of Weyl fermions and the chiral anomaly on the phonon charge and dispersion?

Theoretical approach

- Two methods:
  1) Integrate-out electrons to get an effective action for phonons.
  2) Semiclassical analysis: Boltzmann equation plus elasticity theory.
- External magnetic field (perturbatively or through Landau levels)
- Interactions: electron-phonon, electron-electron.
- Disorder.

Signatures of the chiral anomaly in optical phonons

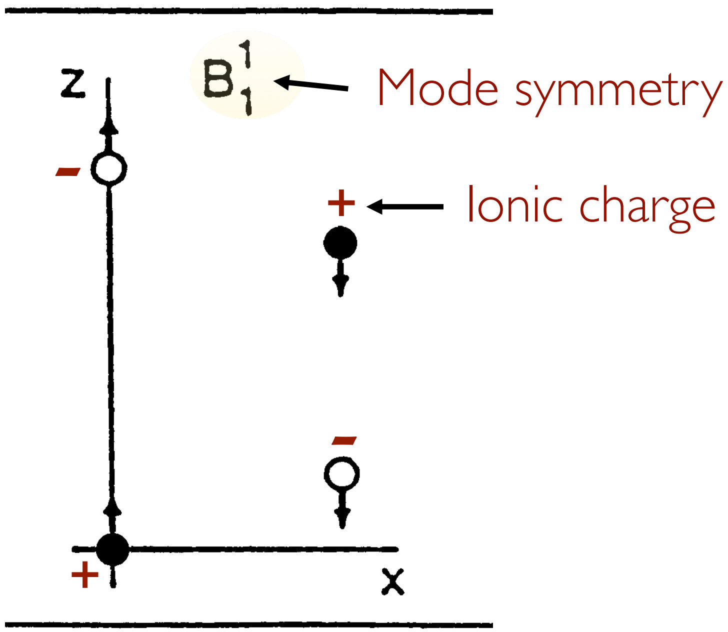
Rinkel, Lopes and Garate, PRL 119, 107401 (2017).

Rinkel, Lopes and Garate, Phys. Rev. B 99, 144301 (2019).

See also: Song et al., PRB 94, 214306 (2016)

Phonon effective charge: Definition

- Change in the unit cell dipole moment due to ion vibrations

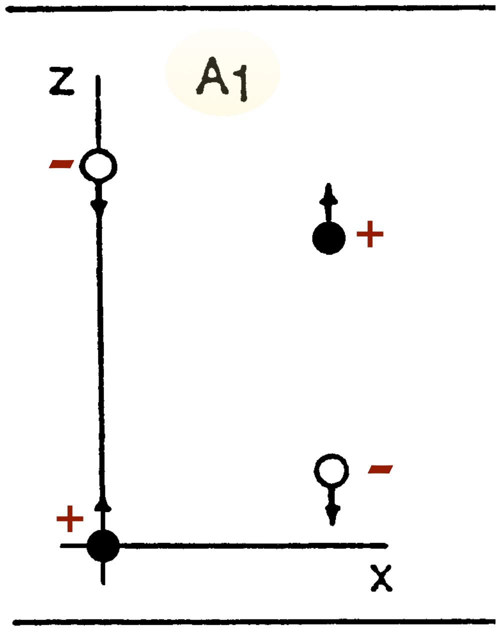


Mode symmetry

Ionic charge

$Q=0$

Infrared (IR) inactive mode



$Q \neq 0$

Infrared (IR) active mode

Stroscio and Dutta,
Phonons in Nanostructures
(Cambridge, 2001)

- Condition for photon absorption: $\mathbf{Q}u \cdot \mathbf{E}_{\text{em}} \neq 0$

Phonon charge: Macroscopic considerations

- Total phonon charge:

Electrical polarization of the unit cell

$$\mathbf{Q} = \frac{\partial \mathbf{P}}{\partial u}$$

- Contribution from the chiral anomaly to the phonon charge:

$$\mathbf{Q}_{\mathrm{ax}} = \frac{\partial^2 \mathcal{L}_{\mathrm{ax}}}{\partial u \, \partial \mathbf{E}} = \boxed{\frac{\partial \theta}{\partial u}} \mathbf{B}$$

$\neq 0$ for pseudoscalar or pseudovector phonons

- Where can one find pseudoscalar/pseudovector phonons?

Phonon charge: Group theoretical considerations

- B-induced Q is not by itself a signature of chiral anomaly.
- Crystals of any symmetry *may* have a pseudoscalar phonon.

Anastassakis *et al*., J. Phys. Chem Solids 33, 1091 (1972).

- If the crystal is chiral (no inversion and no mirrors), then A_1 phonons are pseudoscalar.
- If the crystal is nonchiral, then pseudoscalar phonons exist provided that the atoms of the crystal sit a low-symmetry locations.

Song et al., PRB 94, 214306 (2016)

- For pseudovector phonons, the crystal needs to break time reversal symmetry.

Phonon charge: Microscopic considerations

- Example: pseudoscalar phonon in time-reversal symmetric WSM, at weak B:

Electron charge

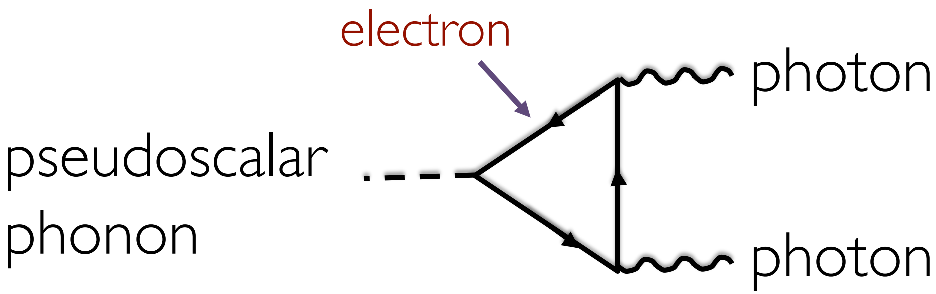
Optical deformation potential (pseudoscalar part)

$$\mathbf{Q}_{\mathrm{ax}}(\mathbf{q},\omega) = i\frac{e^2a^2}{\pi h}\frac{D_z\hbar\omega}{\boxed{(\hbar\omega)^2-(\hbar v_F\mathbf{q})^2}}\mathbf{B}$$

Lattice constant

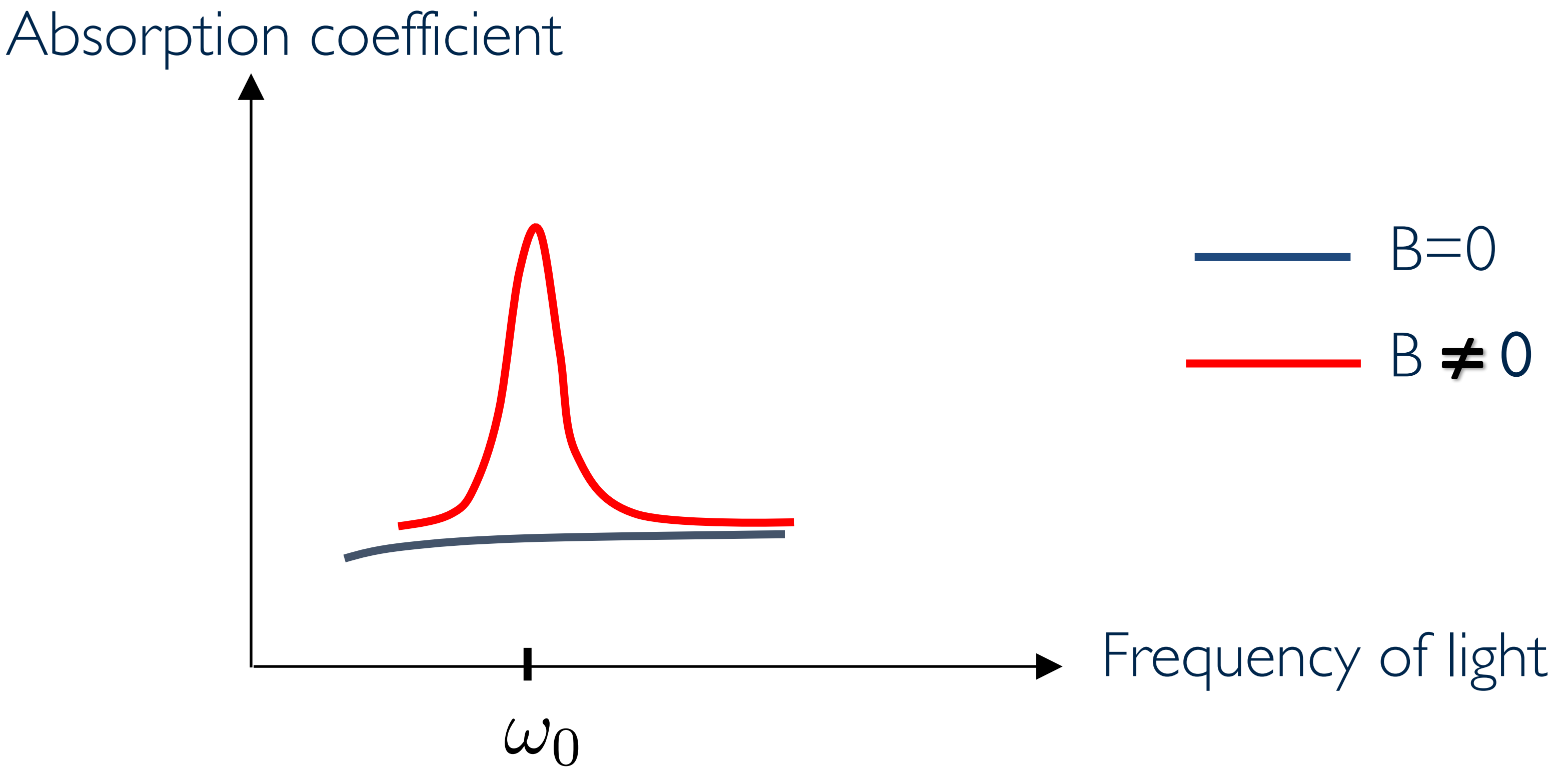
Pole at $\omega = v_F\, q$
(fingerprint of the chiral anomaly)

- Origin of the denominator: triangle diagram



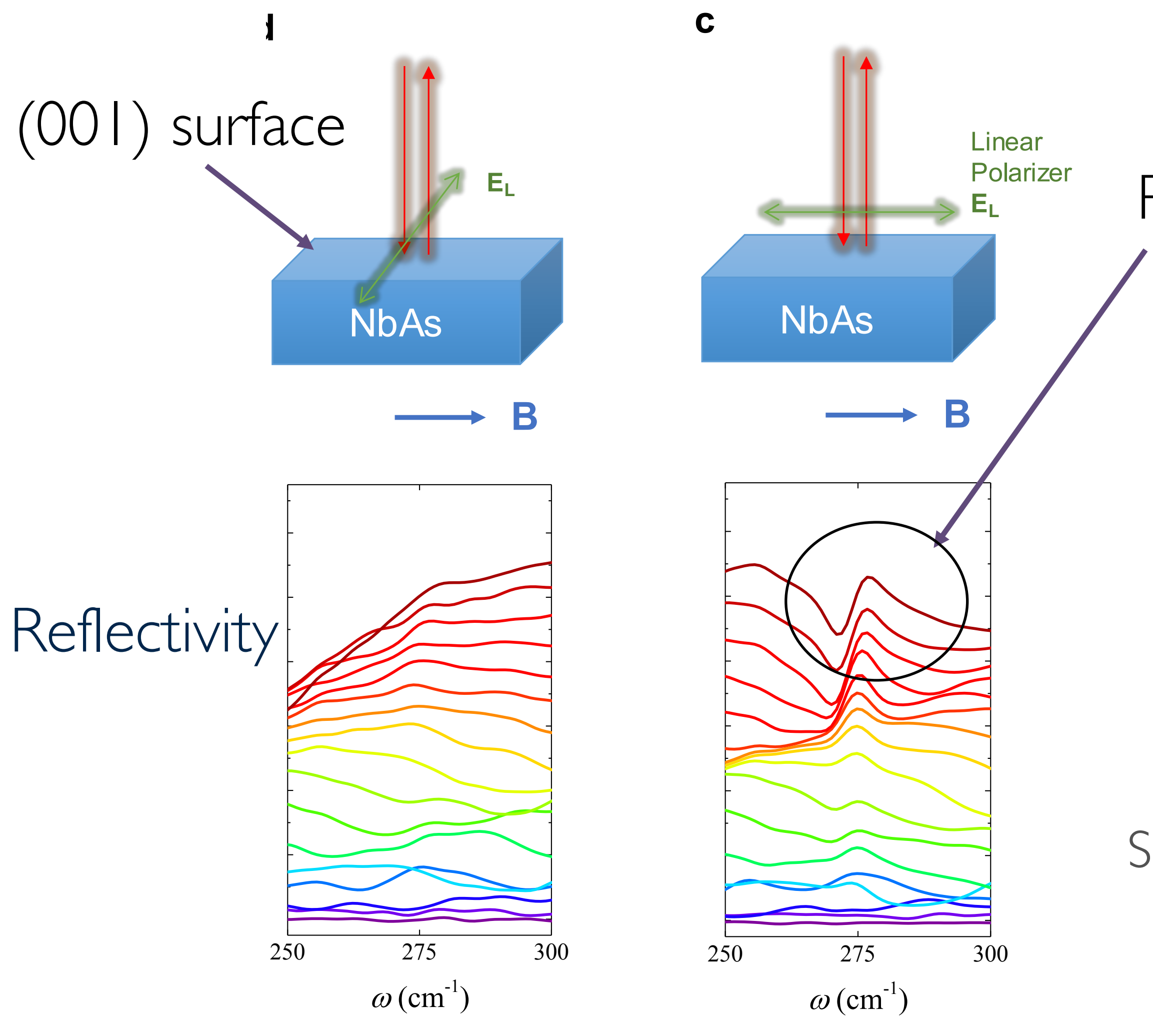
Field-induced infrared absorption

- Consider a long-wavelength pseudoscalar optical phonon of frequency ω_0 that is IR inactive in the absence of a magnetic field.



Field-induced infrared absorption

- Experimental data in NbAs Courtesy of Xiang Yuan (Fudan University) *et al.*; unpublished



Peak in optical reflectivity when $\mathbf{E}_{\rm em} \cdot \mathbf{B} \neq 0$

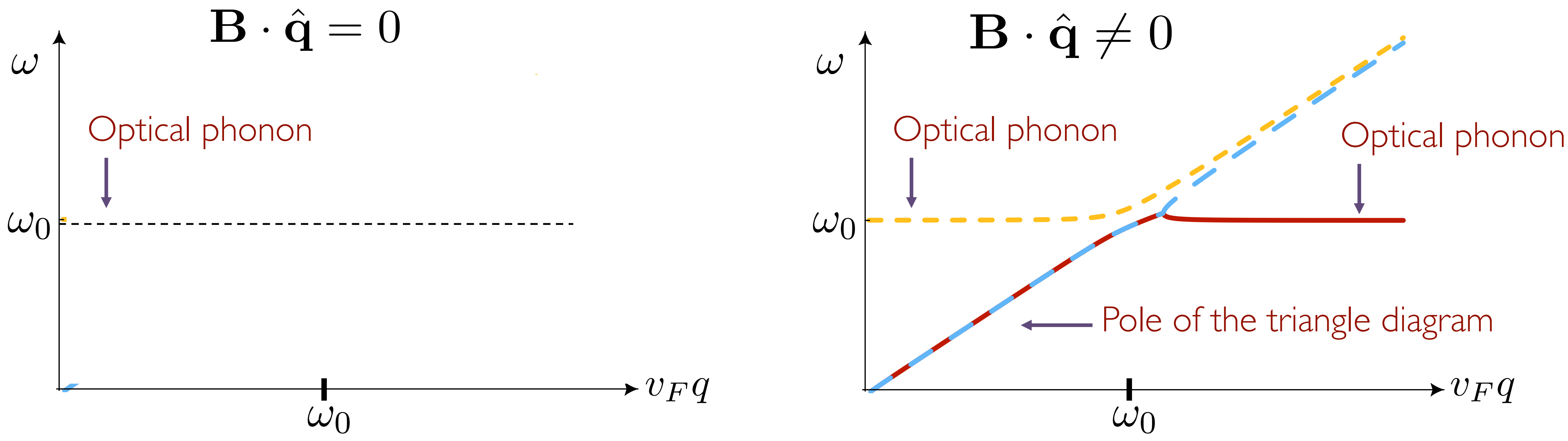
Interpretation: Q || B

Problem: no pseudoscalar phonons in NbAs.

Possible solution: B reduces crystal symmetry

See also Hui, Zhang and Kim, Phys. Rev. B 100, 085144 (2019).

Field-induced features in phonon dispersion

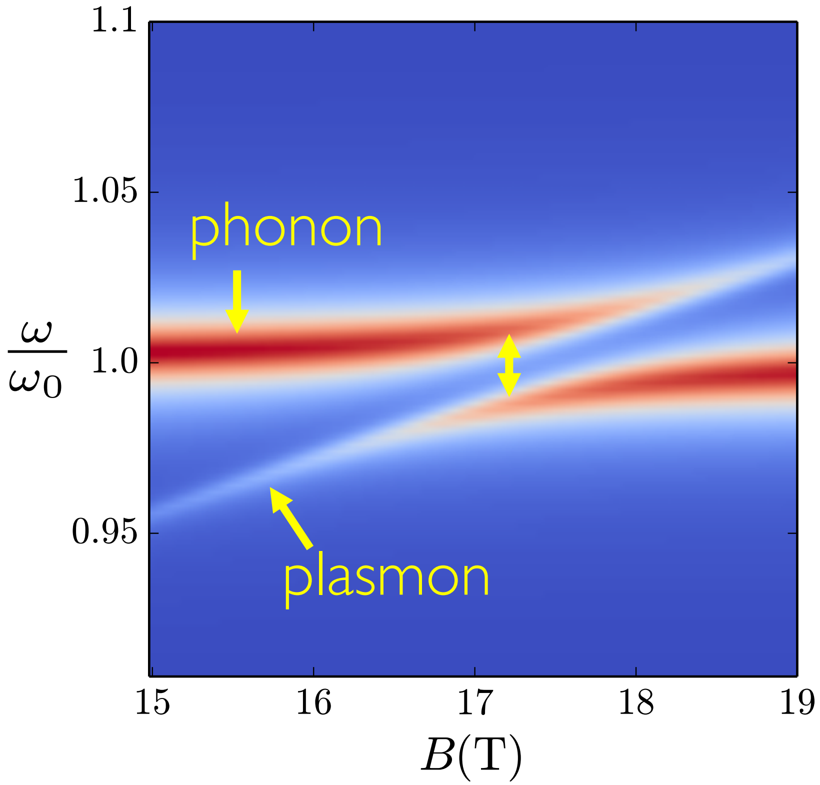


- The hybridization between optical phonon and the pole of the triangle diagram when B is parallel to the phonon's E-field is a smoking gun signature of the chiral anomaly.
- Calculation done to 1st order in perturbation theory in B, at zero temperature and zero chemical potential.

Field-induced features in phonon dispersion

- At strong B field, the character of the anticrossing changes.

The hybridization is now between the optical phonon and the plasmon.



Phonon spectral function (fixed q)

Hybridization gap: $\frac{D_z}{\pi a}\sqrt{\frac{eB}{2\rho v_F}}$

mass density

Estimate of gap: 0.5 meV at strong fields

Signatures of the chiral anomaly in acoustic phonons

Rinkel, Lopes and Garate, Phys. Rev. B 99, 144301 (2019).

Sengupta, Lhachemi and Garate, in preparation.

See also: Spivak and Andreev, Phys. Rev. B 93, 085107 (2016).

Cortijo *et al*., Phys. Rev. Lett. 115, 177202 (2015).

Chernodub and Vozmediano, arXiv: 1904.09113.

Sound velocity in a piezoelectric WSM (e.g. TaAs)

- Consider scalar phonons in a nonchiral WSM

Piezoelectric coupling

$$v = \sqrt{v_0^2 + \frac{d^2}{\rho \epsilon_\infty \epsilon}}$$

Screening from electrons near the Fermi energy
("longitudinal dielectric function")

Sound velocity in the absence of piezoelectricity

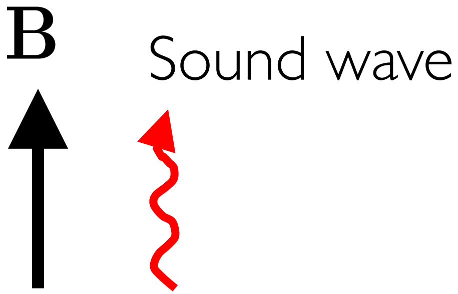
Screening from electrons far from the Fermi energy

Conductivity tensor

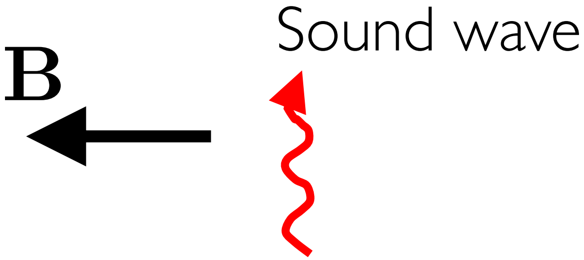
- Link between sound velocity and conductivity: $\epsilon = 1 + i\frac{\mathbf{q}\cdot\boldsymbol{\sigma}\cdot\mathbf{q}}{\omega|\mathbf{q}|^2\epsilon_\infty}$

Signatures of chiral anomaly in sound velocity

- Acoustic counterpart of negative longitudinal magnetoresistance:



Sound velocity decreases with B



Sound velocity increases with B
(or at least decreases much more slowly)

- Contribution from chiral Landau levels to screening:

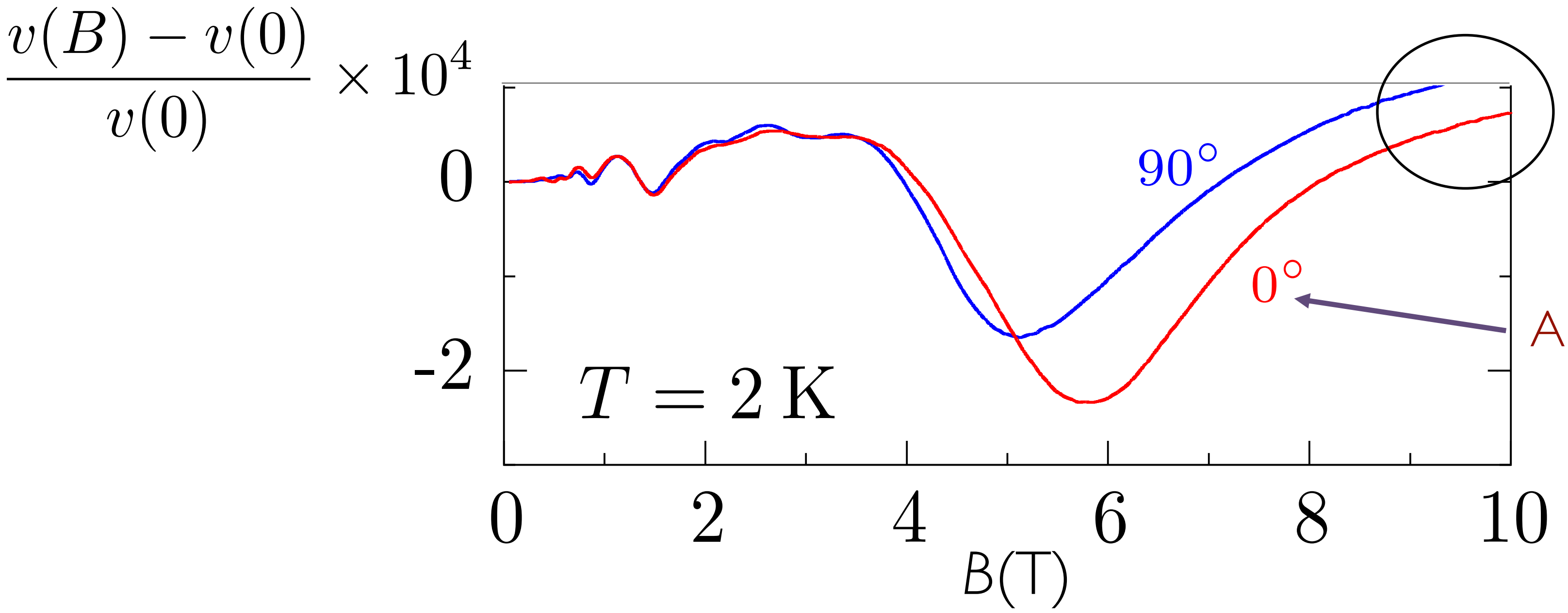
$$\epsilon_{CLL} = 1 + i\sigma_{zz}\cos^2\theta/(\epsilon_\infty \omega)$$

Angle between B and **q**

→At very high B, expect sound velocity to be higher when **B** and **q** are perpendicular.

Signatures of chiral anomaly in sound velocity

- Ultrasound velocity measurements in TaAs: Laliberté *et al*., arXiv: 1909.04270



Angle between **B** and **q**

- At high B, sound travels more slowly along **B** than perpendicular to **B**

- No evidence for acoustic counterpart of negative longitudinal magnetoresistance.

Phonon magnetochiral effect

Sound velocity: *v*

Sound attenuation: *A*

Sound velocity: *v’* ≠ *v*

Sound attenuation: *A’* ≠ *A*

- First experimental observation: Nomura *et al*., Phys. Rev. Lett. 122, 145910 (2019)

Chiral ferromagnet Cu_2OSeO_3. Chiral magnons → chiral phonons

Magnon-phonon hybridization

Phonon magnetochiral effect in chiral WSM

- Candidates: CoSi, RhSi, $SrSi_2\ldots$

electron-phonon coupling

Chiral electrons → chiral phonons (not restricted to Weyl semimetals)

Pseudoscalar part of the acoustic deformation potential

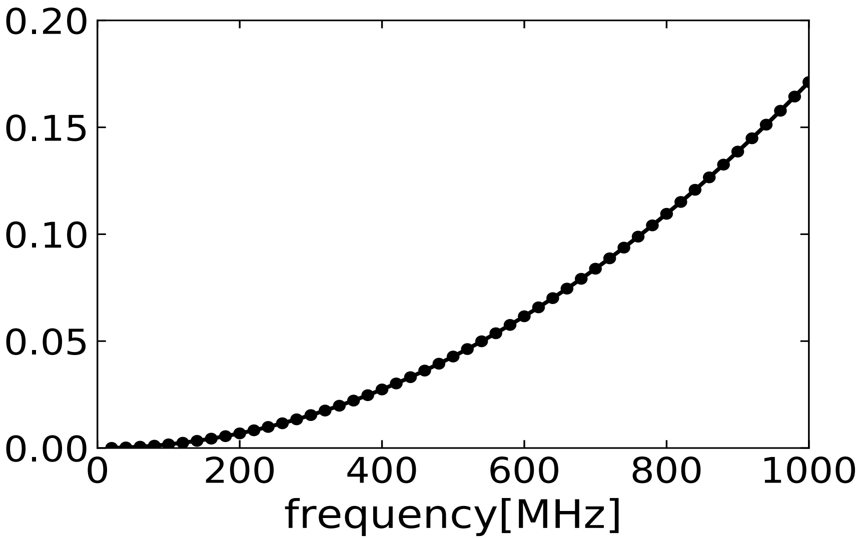
$$A' - A \propto B|C|D_z q_z^2 \mathrm{sg}(q_z)\tau_E$$

Internode relaxation time

Absolute value of Chern number

$$(A' - A)\boxed{\frac{L}{v}}$$

Time-of-travel through sample (L=1 cm)



Some parameter values:

$$B = 1\mathrm{T}$$
$$D_0 = 1.25\mathrm{eV}$$
$$D_z = 0.25\mathrm{eV}$$
$$\hbar/\tau_E = 0.01\mathrm{meV}$$

Conclusions

- We have investigated the influence of chiral anomaly in phonons.

  Rinkel, Lopes and Garate, PRL 119, 107401 (2017).

  Rinkel, Lopes and Garate, Phys. Rev. B 99, 144301 (2019).

  Sengupta, Lhachemi and Garate (manuscript in preparation)

- To do: find out phonon signatures in more generic topological phases.

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