Three-dimensional Dirac semimetal and magnetic quantum oscillations in Cd_3As_2

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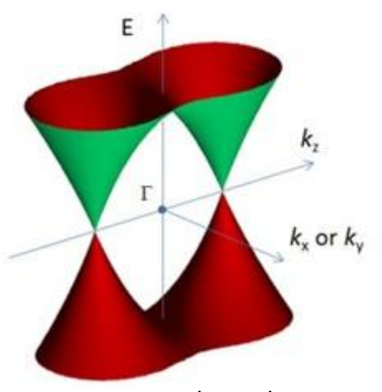
Dirac semimetals



- Linear (Dirac) dispersion in bulk states ⟶ 3D analogue of graphene.

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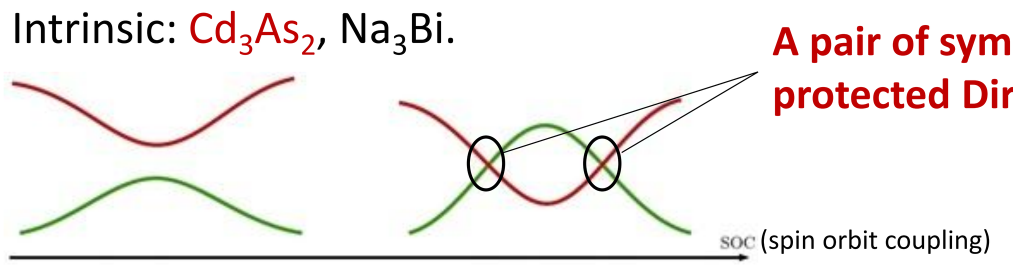
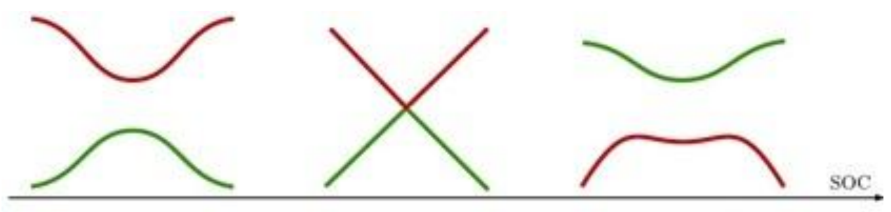
- The inverted band structure (nontrivial topology) with the valence and conduction bands that touch in Dirac points.
- Intrinsic: Cd_3As_2, Na_3Bi.



Trivial insulator Dirac semimetal

- At the phase transition between normal and topological insulator.



Trivial insulator Dirac semimetal Topological insulator

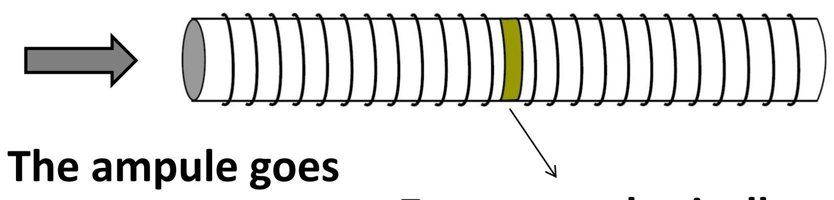
⟹ **Dirac fermion physics**
- High bulk carrier mobility and low effective mass.
- Interesting quantum transport properties.
- A possibility of realizing the Weyl fermion.

Synthesis of Cd_3As_2

- The vapour transport technique is used.
- Crystals grow in the vacuum seald quartz tube, 10 cm long and 16 mm in diameter.
- The modified two zone tube furnace is used.
- The temperature gradient of 585-565 °C is gradually established with the rate of 1.7 °C/h, 8 hours at this gradient and then slowly cooled down to a room temperature.

Sealing of the quartz tube.

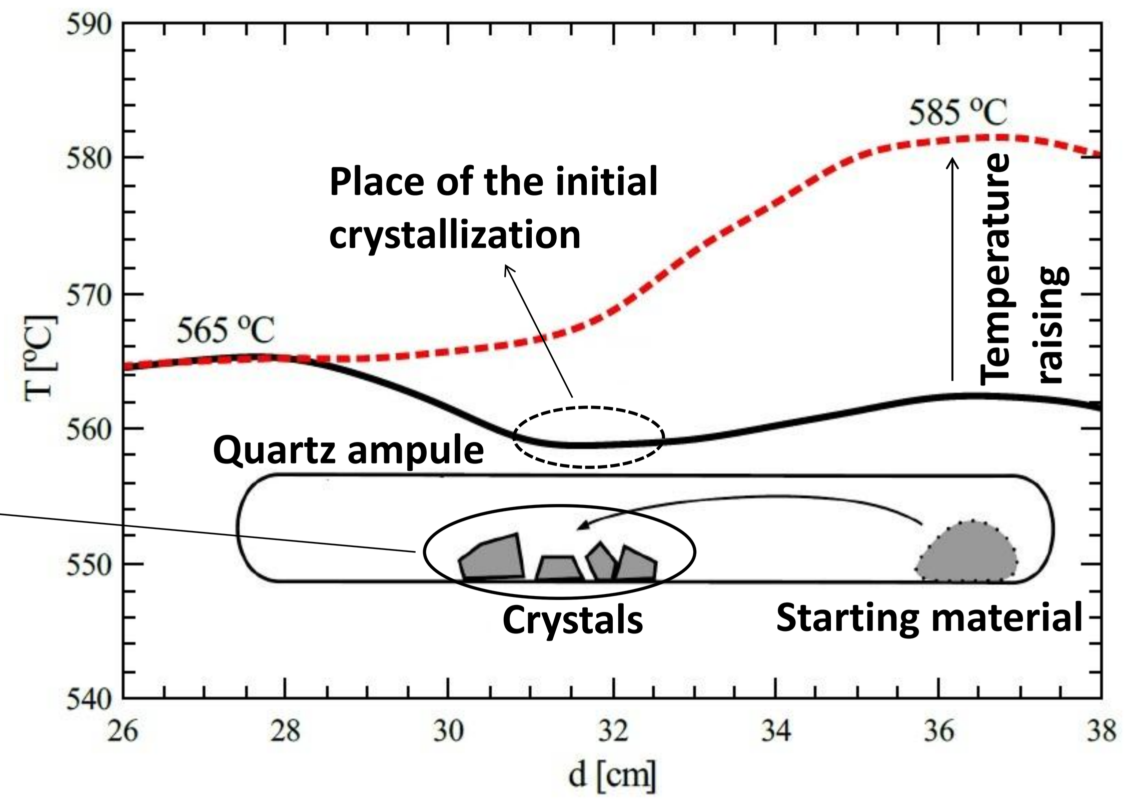
The vacuum sealed quartz ampule with cca 2 g of the polycrystalline Cd_3As_2.



The ampule goes in the tube furnace

Zones are physically separated with the quartz wool.

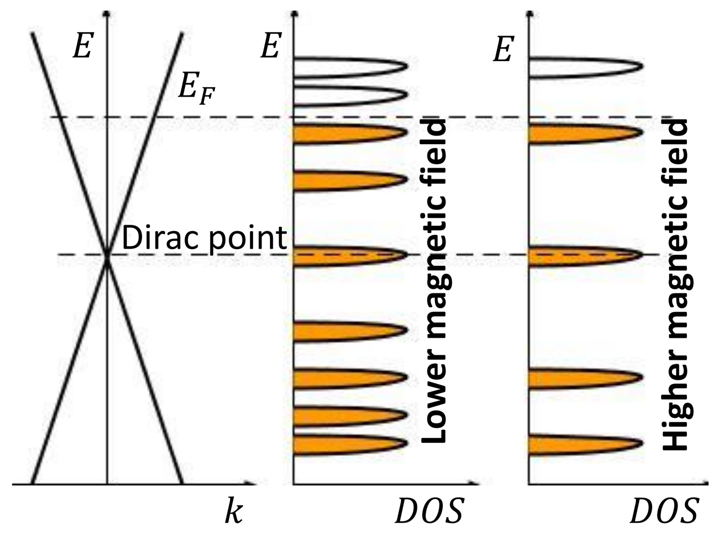
Crystals of Cd_3As_2 in the ampoule.



The temperature profile of the two zone furnace.

Quantum oscillations

- Electrons in strong magnetic field ⟶ Landau quantization of electron states.



Landau levels for Dirac electrons.

Oscillation of physical quantities in $1/B$.

- Magnetoresitivity (Shubnikov de Haas effect).
- **Magnetization (de Haas van Alphen effect).**

Lifshitz-Kosevich formula

$$M_{osc} = A_0 A_T A_D A_S \sin\left[2\pi\left(\frac{F}{B} \pm \frac{1}{8} + \beta\right)\right]$$

$$A_T = \sqrt{B}\frac{\frac{\alpha T}{B}}{\sinh\left(\frac{\alpha T}{B}\right)}$$

$$A_D = e^{-\frac{\alpha T_D}{B}}$$

$$A_S = \cos\left(\frac{\pi}{2} g \frac{m_c^*}{m_e}\right)$$

The Berry phase/2π. **0.5 for Dirac electrons, 0 for Schrödinger electrons.**

$$F = \frac{\hbar}{2e} k_F^2$$

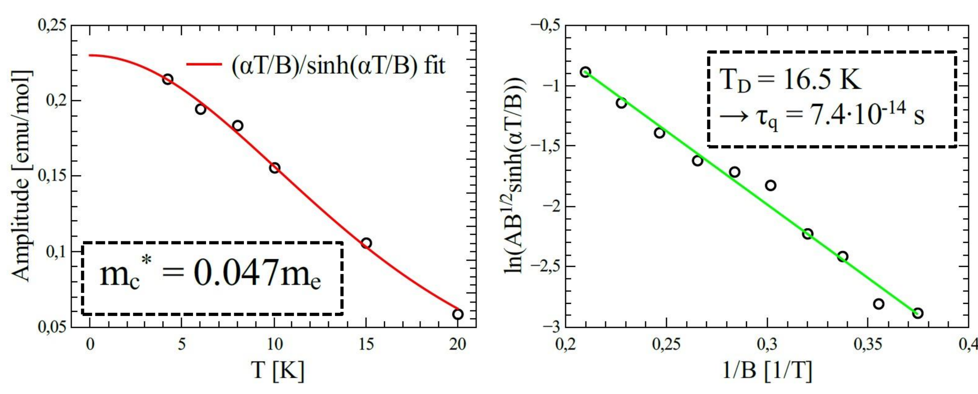
Informations about carrier density and Fermi surface shape.

$$\alpha = 14.69 \frac{m_c^*}{m_e} \mathrm{TK}^{-1}$$ ⟶ **Effective cyclotron mass.**

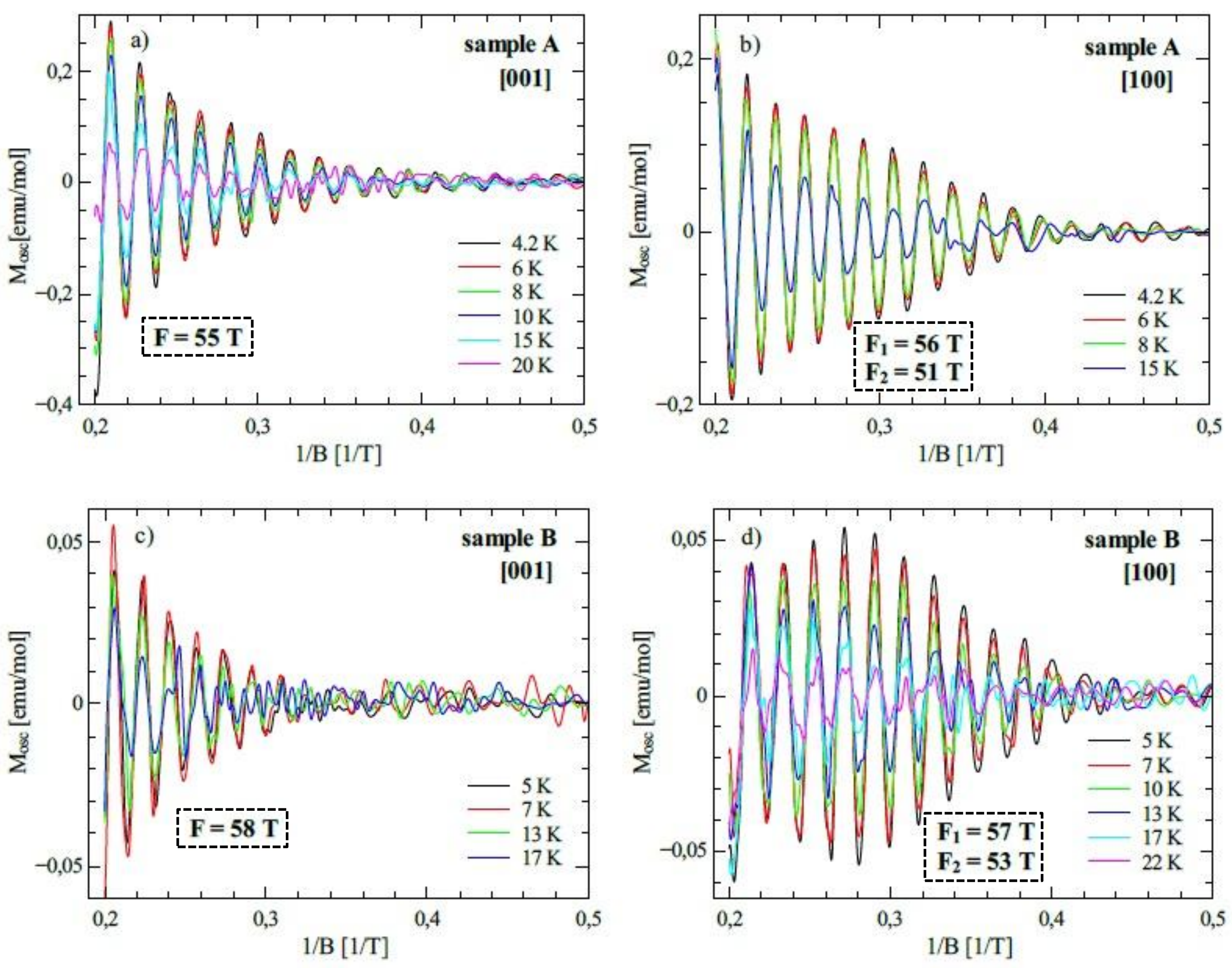
$$T_D = \frac{\hbar}{2\pi k_B \tau}$$ ⟶ **Quantum scattering time.**

Magnetization measurements

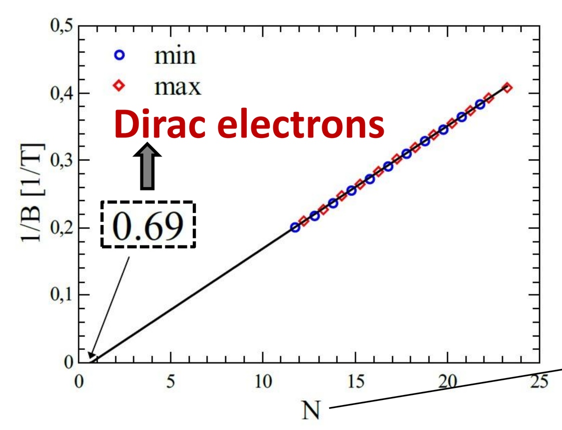
- Two samples: $m = 82$ mg (sample A) and $m = 124$ mg (sample B).
- The magnetization was measured by SQUID magnetometer.
- The magnetic field along [001] and [100] direction.
- From 4.2 − 300 K in magnetic field up to 5 T.
- From 25 − 4.2 K we observe the de Haas van Alphen oscillations.



From A_T and A_D the effective cyclotron mass and Dingle temperature (quantum scattering time) can be obtained.



Landau level (LL) diagram – gives the Berry phase of electrons.



Index corresponding to minima and maxima of oscillations.

The intercept for $1/B = 0$ is near $-\frac{1}{8}$ or $\frac{3}{8}$ (maximal Fermi surface cross section) and $\frac{1}{8}$ or $\frac{5}{8}$ (minimal Fermi surface cross section) for Schrödinger and Dirac electrons, respectively.

Measured dHvA oscillations for two samples and different field directions.

- A single frequency for field along [001] direction.
- Contributions of two close frequencies for field along [100] direction.
- Frequencies are obtained by direct fitting to the two frequency LK formula.

$$F = 55\,\mathrm{T} \Longrightarrow \begin{matrix} k_F = 0.041\,\mathrm{\mathring{A}}^{-1} \\ n = 2.3\cdot10^{18}\,\mathrm{cm}^{-3} \\ E_F = 270\,\mathrm{meV} \end{matrix}$$

Conclusion

- Single crystals of Cd_3As_2 are successfully synthesized by the modified vapor transport techinque.
- Samples were characterized by magnetization measurements and dHvA oscillations are observed below 25 K.
- We obtained single frequency dHvA oscillations for magnetic field along [001] direction, whereas for field in [100] direction the contributions of two close frequencies are observed.
- The dHvA oscillations are modeled by LK formula.
- From LL diagram, for single frequency quantum oscillations, a nontrivial π Berry phase is found confirming the existence of the Dirac fermion in Cd_3As_2.

Acknowledgments

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