Iowa State University

Department of Physics and Astronomy

Nodeless superconductivity in type-II Dirac semimetal $PdTe_2$: London penetration depth and pairing-symmetry analysis

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In collaboration with S. Teknowijoyo[1, 2], N. H. Jo[1, 2], M. S. Scheurer[3], M. A. Tanatar[1, 2], K. Cho[1, 2], S. L. Budko[1, 2], P. C. Canfield[1, 2] and R. Prozorov[1, 2]

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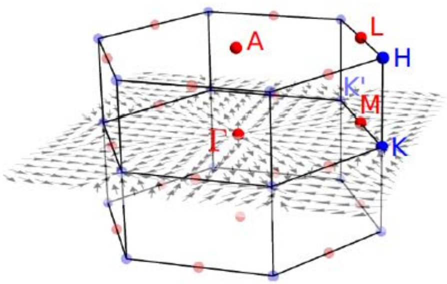
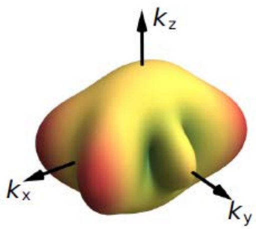
Superstripes Conference, Ischia, June 26, 2019





Reference:

S. Teknowijoyo *et al.*, Phys. Rev. B **98**, 024508 (2018).

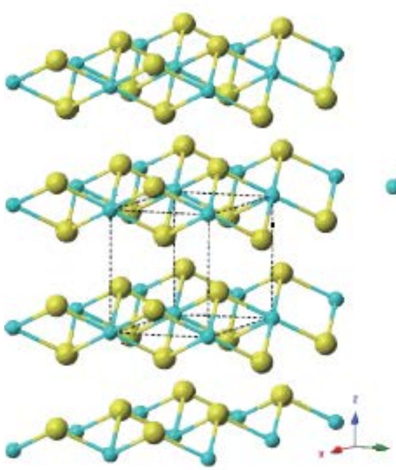
Funding:

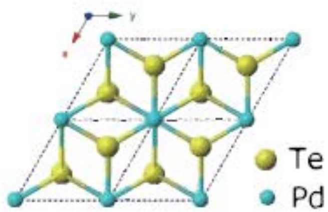
DOE Ames Lab

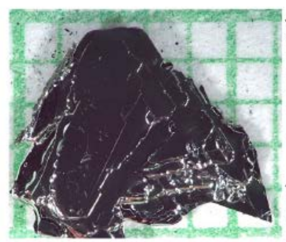
GORDON AND BETTY MOORE FOUNDATION

Leopoldina Nationale Akademie der Wissenschaften

$PdTe_2$: electronic structure



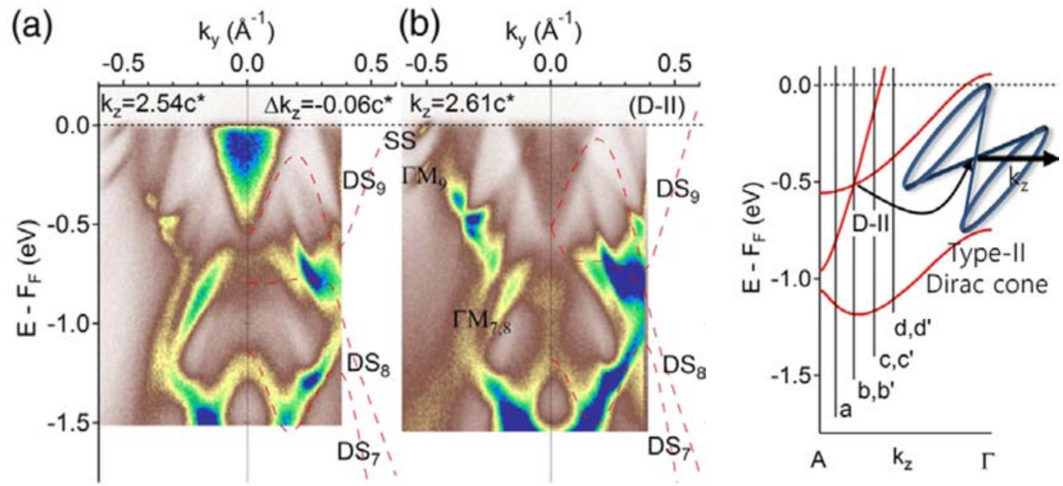




$P\bar{3}m1(164)$

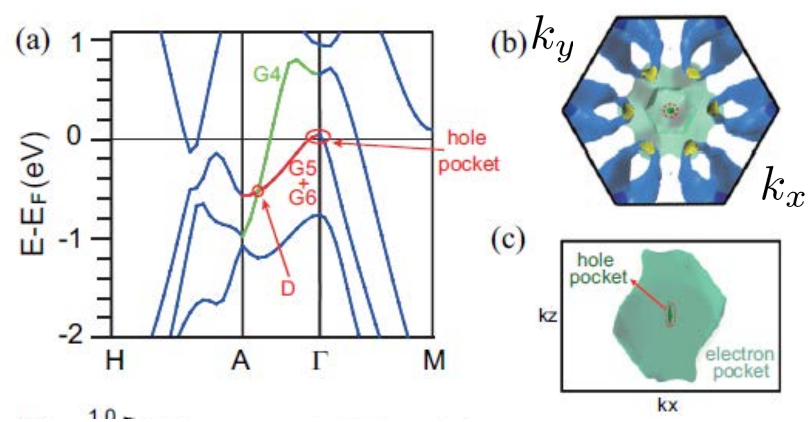
Single crystals

ARPES [1]:



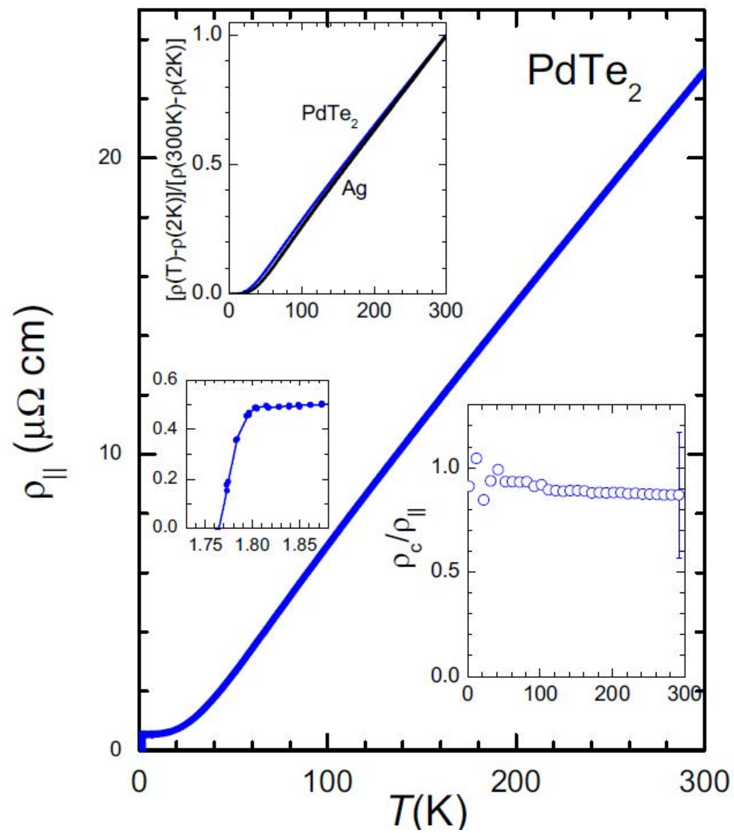
- Tilted Dirac dispersion (type-II)
  - Dirac point located at $\mathrm{k} = (0,0,\pm 0.4)$
  - 0.5 eV below E_F
- Fermi surface (at E_F):
  - Hole and electron pocket at Γ
  - Electron pockets at K, K'
- Surface states seen in ARPES

First-principles [2]:



[1] H.-J. Noh *et al.*, PRL (2017); [2] F. Fei *et al.*, (2017)

$PdTe_2$: transport and superconductivity



From [1]

- Linear-T resistivity above 40 K (dominantly phonon scattering)
- Isotropic resistivity: small anisotropy is T-independent ⇢ 3D material
- Flat plateau below 10 K
- Superconducting transition at T_c=1.7 K [2]
- Note: robust surface superconductivity reported by de Visser group [3, 4]

Superconductivity in material with strong spin-orbit coupling and Dirac node

[1] S. Teknowijoyo *et al.*, PRB, (2018);
[2] J. Guggenheim *et al.*, Helv. Phys. (1961);
[3] Leng *et al.*, PRB (2017);
[4] Leng *et al.*, arXiv (2019).

Questions:

- Symmetry of SC pairing state
- Topology of the superconducting state
- Pairing mechanism

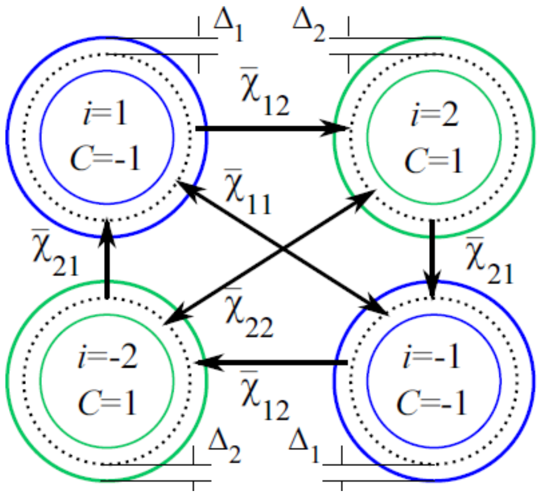
Topological SC in Dirac and Weyl semimetals

Potential path to topological superconductivity

➢ Induce SC in system with non-trivial normal state topology [1]

- Time-reversal symmetric SC: Class DIII, index Z in 3D
  ⇢ topological full gap SC possible
- Time-reversal breaking SC: Class D, trivial in 3D
  ⇢ topological SC only possible for nodal SC

Natural candidate: Weyl semimetal borne out of Dirac semimetal



From Hosur *et al.*, PRB (2014).

- Weyl SM show non-zero Chern number

Breaking inversion: Full-gap topological p-wave SC predicted for unconventional mechanism ($s^{\pm}$): $sign(\Delta_1) \neq sign(\Delta_2)$ [2]

$$\nu = \frac{1}{2} \sum_s \mathrm{sign}\left(\widetilde{\Delta}_s(\boldsymbol{k}_s)\right) C_{1,s}$$

[1] X.-L. Qi *et al.*, PRB (2010); [2] P. Hosur *et al.*, PRB (2014).

Topological SC in Dirac and Weyl semimetals

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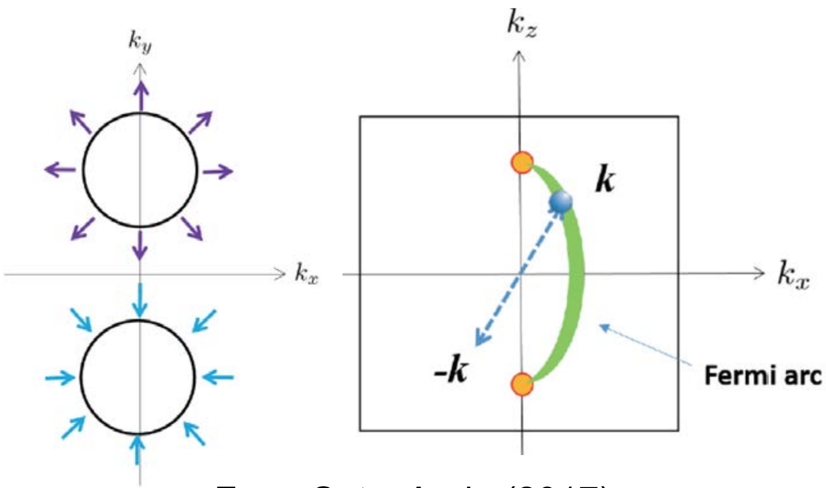

From Sato, Ando (2017).

Breaking time-reversal symmetry:

- Non-trivial topology only for nodal gap
- Spin structure on Fermi surface favors odd-parity pairing [2]
- Nodal topological SC predicted with Fermi arc surface states [2, 3]

[1] X.-L. Qi *et al.*, PRB (2010); [2] Sato, Ando, Rep, Prog. Phys. (2017); [3] T. Meng, L. Balents, PRB (2012).

Superconducting pairing states in $PdTe_2$

IR	Pairing	d_n	TRS	Order parameter $\Delta i\sigma_y$
A_{1g}	s wave	1	y	$a + b(X^2 + Y^2) + cZ^2$
A_{2g}	g wave	1	y	$XZ(X^2 - 3Y^2)$
E_g	$e_{g(1,0)}$ wave	2	y	$a(X^2 - Y^2) + bYZ$
E_g	$e_{g(0,1)}$ wave	2	y	$aXY + bXZ$
E_g	$e_{g(1,i)}$ wave	2	n	$a(X + iY)^2 + bZ(Y + iX)$
A_{1u}	p wave	1	y	$a(X\sigma_x + Y\sigma_y) + bZ\sigma_z$
A_{2u}	p wave	1	y	$a(Y\sigma_x - X\sigma_y) + bX(X^2 - 3Y^2)\sigma_z$
E_u	$e_{u(1,0)}$ wave	2	y	$aX(X^2 - 3Y^2)\sigma_x + bZ\sigma_y + cY\sigma_z$
E_u	$e_{u(0,1)}$ wave	2	y	$aZ\sigma_x + bX(X^2 - 3Y^2)\sigma_y + cX\sigma_z$
E_u	$e_{u(1,i)}$ wave	2	n	$[aZ + ibX(X^2 - 3Y^2)](\sigma_x + i\sigma_y) + c(X + iY)\sigma_z$

$X = \sin k_x$, etc.

From Teknowijoyo *et al.*, PRB (2018).

- Assume that SC is homogeneous and transition continuous

➢ SC order transforms under one of the IRs

- Inversion symmetry: singlet and triplet don't mix

$$\Delta(\boldsymbol{k}) = (\sigma_0\psi(\boldsymbol{k}) + \boldsymbol{d}(\boldsymbol{k}) \cdot \boldsymbol{\sigma})\, i\sigma_y.$$

- 10 possible pairing states
  - 8 preserve TRS, 2 break TRS

Character table of D_{3d}

	E	$2C_3$	$3C_2$	i	$2S_6$	$3\sigma_d$	Basis functions
A_{1g}	1	1	1	1	1	1	$x^2 + y^2$, z^2
A_{2g}	1	1	−1	1	1	−1	$xz(x^2 - 3y^2)$
E_g	2	−1	0	2	−1	0	$(x^2 - y^2, 2xy)$, (yz, xz)
A_{1u}	1	1	1	−1	−1	−1	$x(x^2 - 3y^2)$
A_{2u}	1	1	−1	−1	−1	1	z
E_u	2	−1	0	−2	1	0	(x, y)

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A_{2u}	p wave	1	y	$a(Y\sigma_x - X\sigma_y) + bX(X^2 - 3Y^2)\sigma_z$
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E_u	$e_{u(0,1)}$ wave	2	y	$aZ\sigma_x + bX(X^2 - 3Y^2)\sigma_y + cX\sigma_z$
E_u	$e_{u(1,i)}$ wave	2	n	$[aZ + ibX(X^2 - 3Y^2)](\sigma_x + i\sigma_y) + c(X + iY)\sigma_z$

$X = \sin k_x$, etc.

From Teknowijoyo *et al.*, PRB (2018).

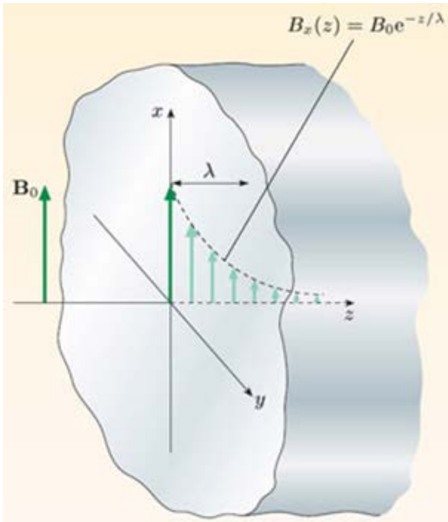
- Assume that SC is homogeneous and transition continuous

➢ SC order transforms under one of the IRs

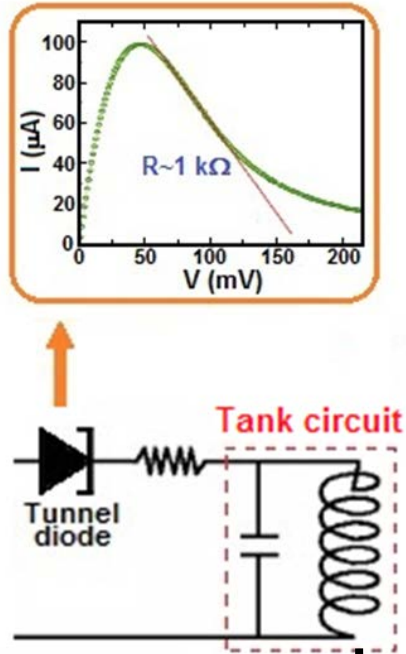
- Inversion symmetry: singlet and triplet do not mix
- 10 possible pairing states
  - 8 preserve time-reversal symmetry, 2 break it

Reduce number of possible states using input from experiment.

Penetration depth λ with tunnel diode resonator



Tunnel diode resonator (TDR)



Resonance frequency

f_0 ~ 14 MHz

Resolution

$\Delta\lambda$ ~ 0.5 Å for sub-mm size crystals

Lowest T

~ 400 mK

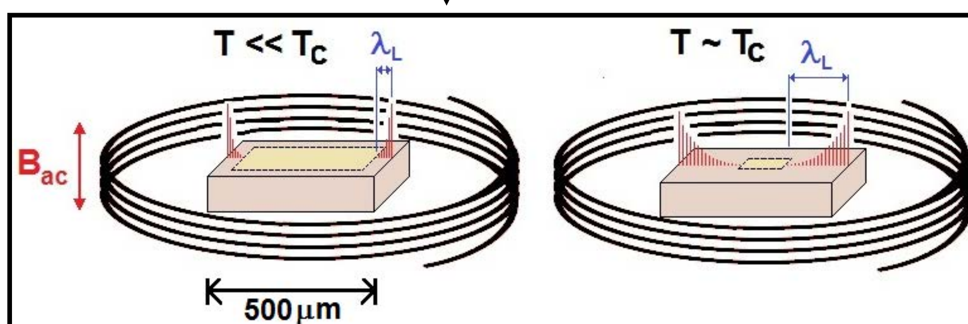
LC Tank Circuit

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \approx 14MHz$$

$$\frac{\Delta f}{f_0} = -\frac{1}{2}\frac{dL}{L_0} = -\frac{1}{2}\frac{V_{sample}}{V_{coil}} 4\pi\chi$$

$$\Delta f(T) = -G4\pi\chi(T) = G[1 - \frac{\lambda}{R}\tanh(\frac{R}{\lambda})]$$

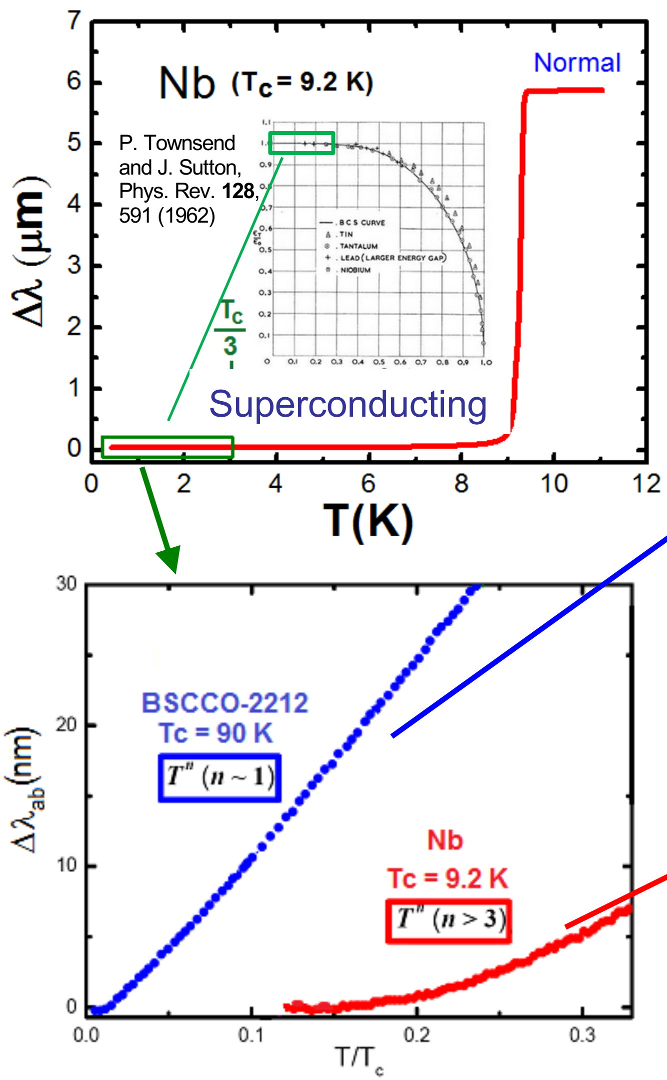
$$\approx G(1 - \frac{\lambda}{R}) \qquad R >> \lambda.$$



R. Prozorov and V. G. Kogan, Rep. Prog. Phys. (2011).

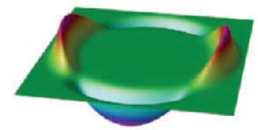
C. T. Van-Degrift, Rev. Sci. Instrum. (1975)

Penetration depth λ using tunnel-diode resonator



Prozorov and Giannetta, *Supercond. Sci. Technol.* **19** R41 (2006)

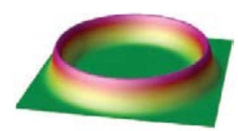
Line nodal gap



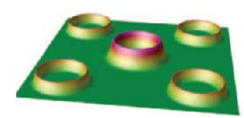
d-wave gap

$\Delta\lambda(T) \sim T^n \ (n \sim 1)$

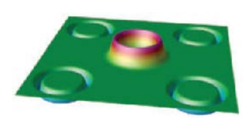
Full gap



s-wave gap



Multiband S_{++}

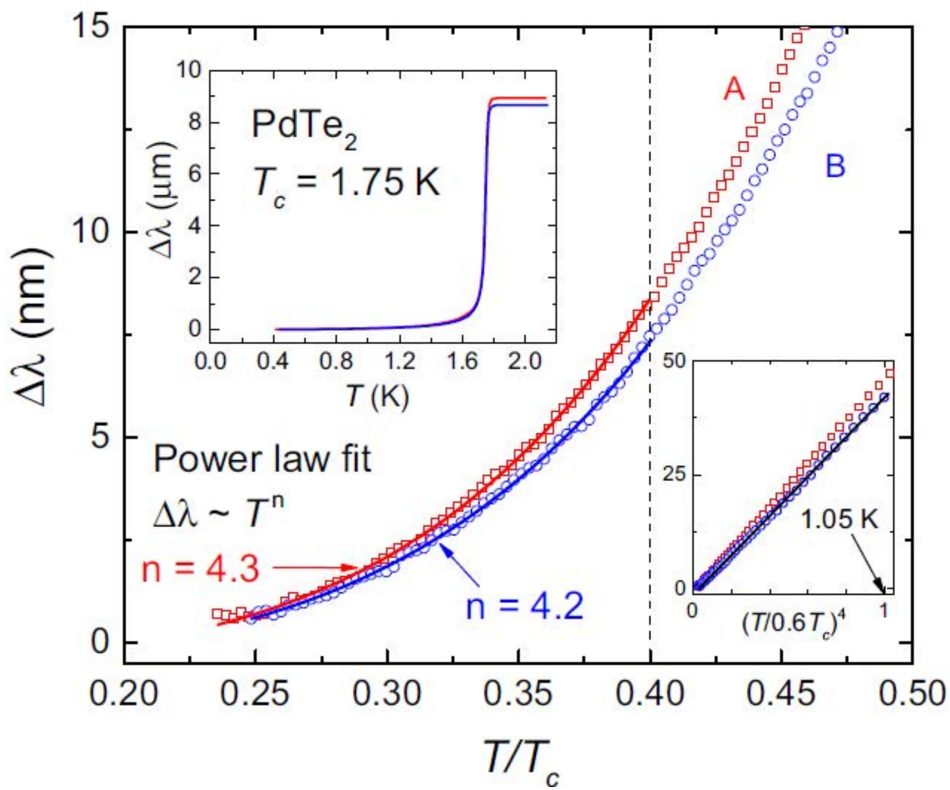


Multiband $S_{\pm}$

$\Delta\lambda(T) \sim T^n \ (n > 3)$

Mazin, Nature (2010)

$PdTe_2$: Low-T London penetration depth Δλ

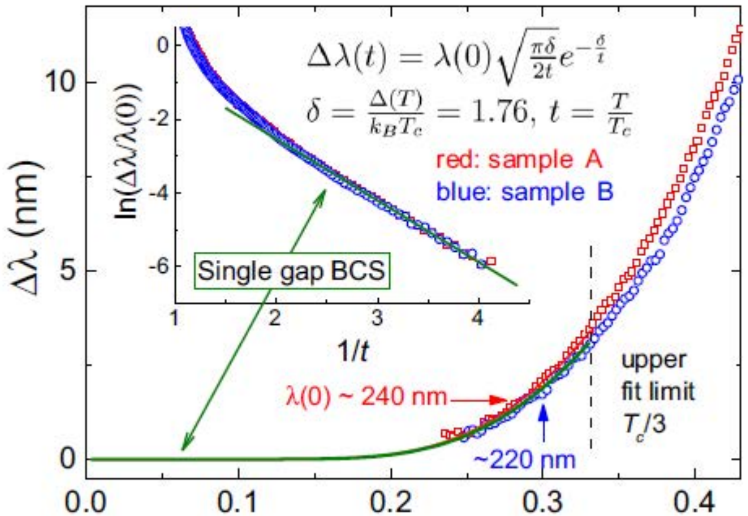


- Power law fit $\Delta\lambda \propto T^n$ gives $n = 4.25$ ⇢ Full gap superconductor
- To extend low temperature fitting range $T < \frac{T_c}{3} = 0.4\ K$, dilution fridge experiments are ongoing

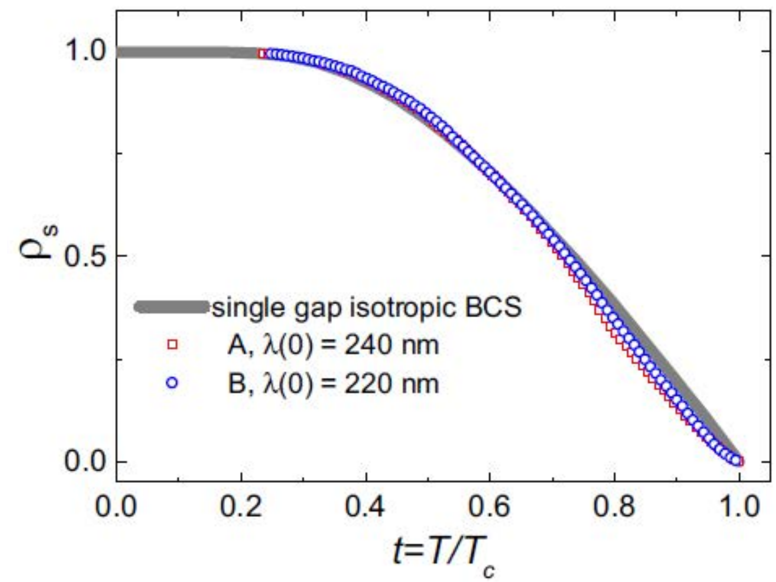
[1] S. Teknowijoyo *et al.*, PRB, (2018).

BCS theory describes London penetration depth

Fit to BCS: exponential



Superconducting density



- T-dependence of $\Delta\lambda$ described by BCS with single, isotropic, full gap
- Fit to BCS yields $\lambda(T=0) = 230\ nm$
- Previously measured coherence length [2]: $\xi = 439\ nm$

Ginzburg-Landau parameter $\kappa = \frac{\lambda}{\xi} = 0.52$: type-I SC
(in agreement with measurements of M and χ [2])

[1] S. Teknowijoyo *et al.*, PRB (2018); [2] H. Leng *et al.*, PRB (2017).

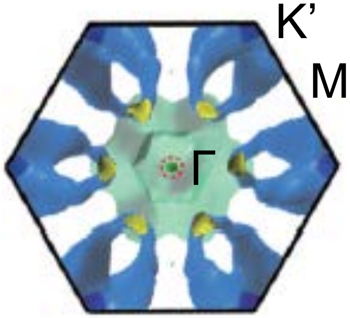
Identify nodeless SC states from symmetry analysis

- Exclude gap functions where symmetry enforces presence of nodes.

Character table of D_{3d}

	E	$2C_3$	$3C_2$	i	$2S_6$	$3\sigma_d$	Basis functions
A_{1g}	1	1	1	1	1	1	x^2+y^2, z^2
A_{2g}	1	1	-1	1	1	-1	$xz(x^2-3y^2)$
E_g	2	-1	0	2	-1	0	$(x^2-y^2, 2xy)$, (yz, xz)
A_{1u}	1	1	1	-1	-1	-1	$x(x^2-3y^2)$
A_{2u}	1	1	-1	-1	-1	1	z
E_u	2	-1	0	-2	1	0	(x,y)

Fermi surfaces around Γ point.



A_{1g} state: (even ⇢ singlet)

- Singlet $\Delta(\boldsymbol{k}) = i\sigma_y \psi(\boldsymbol{k})$
- IR requires $\psi(\boldsymbol{k})$ to be invariant under all elements of D_{3d}
  $\psi(\boldsymbol{k}) = \mathrm{const.} > 0$

Fully gapped A_{1g} (s-wave) state possible.

Identify nodeless SC states from symmetry analysis

- Exclude gap functions where symmetry enforces presence of nodes.

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E_g	2	−1	0	2	−1	0	$(x^2-y^2, 2xy)$, (yz, xz)
A_{1u}	1	1	1	−1	−1	−1	$x(x^2-3y^2)$
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E_u	2	−1	0	−2	1	0	(x, y)

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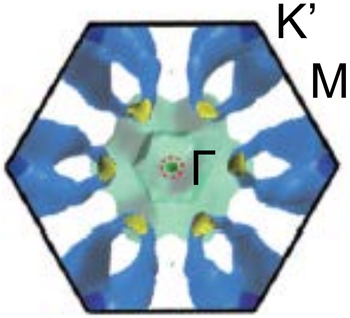

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  $\psi(\boldsymbol{k}) = \text{const.} > 0$

Fully gapped A_{1g} (s-wave) state possible.

A_{2g} state: (even ⇢ singlet)

- Odd under σ_d requires
  $\psi(k_x, k_y, k_z) = -\psi(-k_x, k_y, k_z)$
  - ➢ ψ vanishes in (k_y, k_z) plane
  - ➢ Line node on FS around Γ.
  - ➢ C_3 even ⇢ 2 line nodes
  - ➢ C_2 odd ⇢ 1 line node

A_{2g} (g-wave) state has 4 line nodes imposed by symmetry.

Identify nodeless SC states from symmetry analysis

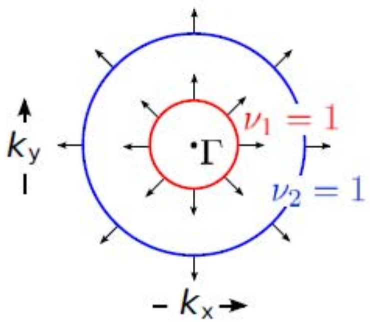
IR	Pairing	d_n	TRS	Order parameter $\Delta i\sigma_y$	Minimal number of nodes per FS	Topology
A_{1g}	s wave	1	y	$a+b(X^2+Y^2)+cZ^2$	0	trivial
A_{2g}	g wave	1	y	$XZ(X^2-3Y^2)$	4 nodal lines	
E_g	$e_{g(1,0)}$ wave	2	y	$a(X^2-Y^2)+bYZ$	2 nodal lines	
E_g	$e_{g(0,1)}$ wave	2	y	$aXY+bXZ$	2 nodal lines	
E_g	$e_{g(1,i)}$ wave	2	n	$a(X+iY)^2+bZ(Y+iX)$	2 nodal points	
A_{1u}	p wave	1	y	$a(X\sigma_x+Y\sigma_y)+bZ\sigma_z$	0	trivial/top.
A_{2u}	p wave	1	y	$a(Y\sigma_x-X\sigma_y)+bX(X^2-3Y^2)\sigma_z$	2 nodal points	
E_u	$e_{u(1,0)}$ wave	2	y	$aX(X^2-3Y^2)\sigma_x+bZ\sigma_y+cY\sigma_z$	0	trivial/top.
E_u	$e_{u(0,1)}$ wave	2	y	$aZ\sigma_x+bX(X^2-3Y^2)\sigma_y+cX\sigma_z$	2 nodal points	
E_u	$e_{u(1,i)}$ wave	2	n	$[aZ+ibX(X^2-3Y^2)](\sigma_x+i\sigma_y)+c(X+iY)\sigma_z$	2 nodal points [44]	

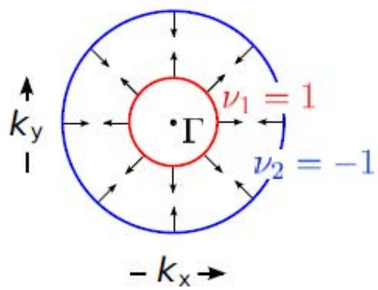
- Only 3 out of 10 states have no symmetry-enforced nodal points or lines.
  - A_{1g}: trivial s-wave state, could be s^{++} or $s^{\pm}$.
  - A_{1u}: odd-parity p-wave state.
    - Balian-Werthamer state on each FS.
    - Can be topologically non-trivial.
    - Fu-Berg criterion [1] not applicable as total number of enclosed TR momenta is even (two FS around Γ).
  - $e_{u(1,0)}$: odd-parity state that transforms as k_x.
    - Anisotropic gap. Can be adiabatically transformed to A_{1u} state.

[1] Fu, Berg PRL (2010).

Topology of odd-parity states

- A_{1u}: odd-parity p-wave state





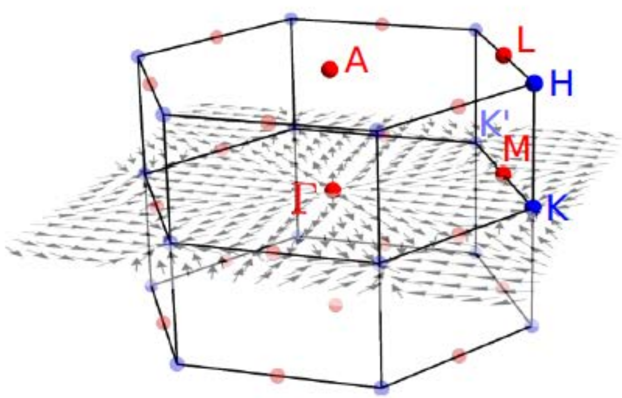
Non-trivial: $\nu_{\text{total}} = 2$ Trivial: $\nu_{\text{total}} = 0$

For each FS obtain ν from

$$\nu = \frac{1}{2}\sum_s \text{sign}\left(\widetilde{\Delta}_s(\boldsymbol{k}_s)\right) C_{1,s}$$

Total topological index

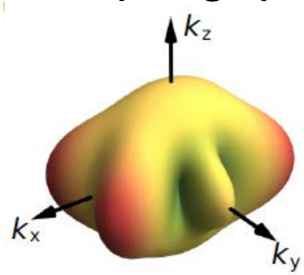
$$\nu_{\text{total}} = \nu_1 + \nu_2$$



Simplest texture of d(k) is non-trivial

- $e_{u(1,0)}$: exhibits anisotropic gap

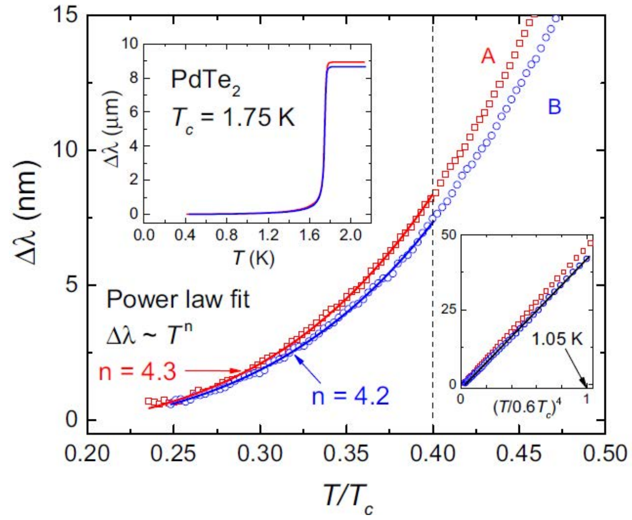
Gap of $e_{u(1,0)}$ state

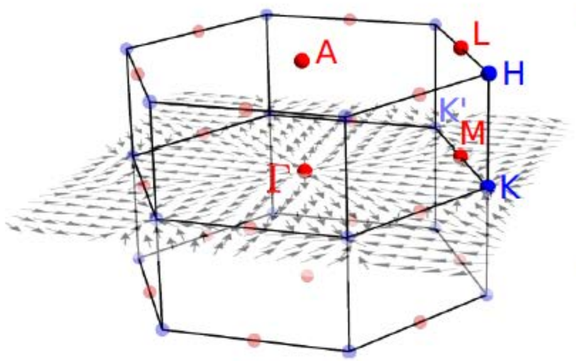


- Unlikely as no anisotropies measured

Summary: $PdTe_2$

- Penetration depth λ ⇢ full SC gap
- Single gap energy scale
- BCS fit gives $\lambda(T=0) = 230\,nm$
- Only 3 possible full-gap pairing states





- A_{1g}: trivial s-wave pairing
- A_{1u}: odd-parity p-wave Balian-Werthamer state
  - Can be topologically non-trivial.
- $e_{u(1,0)}$: odd-parity state equivalent to A_{1u}
  - Anisotropic gap transforming as k_x

Outlook:

- Microscopic theory
- Behavior under disorder
- Surface state SC

Reference:
S. Teknowijoyo *et al.*, PRB **98**, 024508 (2018).

Thank you for your attention!