Interlayer Superconductivity in Graphene Materials

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ISLAMIC REPUBLIC OF
IRAN ایران
National capital
Provincial capital
City, town
Airport
International boundary
Provincial boundary
Main road
Secondary road
Railroad
CASPIAN SEA
PERSIAN GULF
GULF OF OMAN
Strait of Hormuz
TURKMENISTAN
AFGHANISTAN
PAKISTAN
IRAQ
TURKEY
AZERBAIJAN
ARMENIA
KUWAIT
Kuwait
BAHRAIN
Manama
QATAR
Doha
SAUDI ARABIA
UNITED ARAB EMIRATES
Abu Dhabi
OMAN
Baghdad
Tehrān
ĀZARBĀYJĀN-E KHĀVARĪ
ĀZARBĀYJĀN-E GHARBĪ
ARDEBĪL
GĪLĀN
ZANJĀN
MĀZANDARĀN
TEHRĀN
SEMNĀN
KORDESTĀN
HAMADĀN
KERMĀNSHĀH
MARKAZĪ
LORESTĀN
ĪLĀM
ESFAHĀN
KHORĀSĀN
CHAHARMAHĀL VA-BAKHTIYĀRI
KHŪZESTĀN
BOYERAHMAD VA-KOHGILUYEH
YAZD
KERMĀN
FĀRS
BŪSHEHR
HORMOZGĀN
SĪSTĀN VA BALŪCHESTĀN
Tabrīz
Ardabīl
Orūmiyeh
Rasht
Zanjān
Qazvīn
Sārī
Gorgān
Mashhad
Semnān
Sanandaj
Hamadān
Kermānshāh
Arāk
Qom
Ilām
Khorramābād
Esfahān
Shahr-e Kord
Yazd
Ahvāz
Yāsūj
Shīrāz
Kermān
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Badar-e Būshehr
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Bīrjand
Dasht-e Kavīr
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Krasnovodsk
Araks
Aras
Khvoy
Van
ĀZARBĀYJĀN-E KHĀVARĪ
ĀZARBĀYJĀN-E GHARBĪ
ARDEBĪL
Marand
Tabrīz
Āstārā
CASPIAN SEA
Ardabīl
Daryācheh-ye Orūmīyeh (Lake Urmia)
GĪLĀN
Orūmīyeh
Marāgheh
Mīāneh
Rasht
Mīāndowab
Zanjān
Rūdbār
Sakht Sar
Mahābād
Qezel Owzan
Arbīl
Saqqez
ZANJĀN
Āmol
Sārī
MĀZANDARĀN
Qazvīn
KORDESTĀN
TEHRĀN
As Sulaymanīyah
Kirkūk
Sanandaj
Tehrān
HAMADĀN
Sāveh
Hamadān
Qaşr-e Shīrīn
Kermānshāh
Qom
Daryācheh-ye Namak
Malāyer
MARKAZĪ
KERMĀNSHĀH
Arāk
Kāshān
Borūjerd
LORESTĀN
Baghdad
Īlām
Alīgudarz
Khorramābād
ĪLĀM
Najafābād
EŞFAHĀN

Outline

1. Superconducivity in Graphene Materials

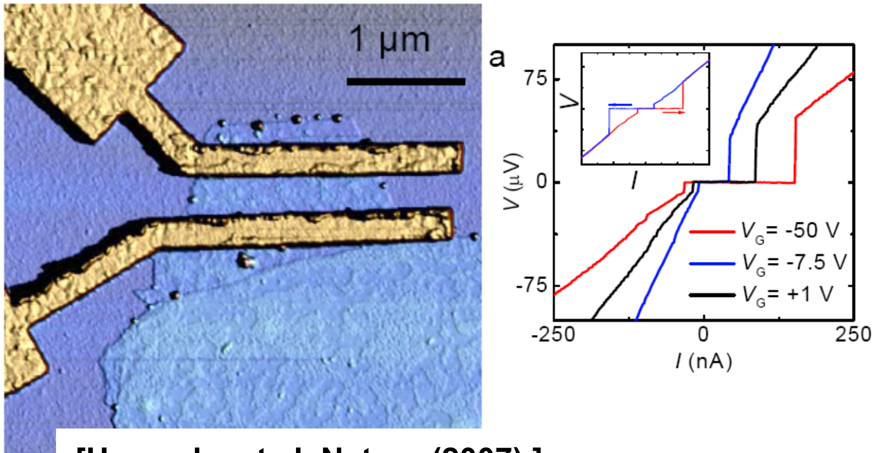
2. BCS theory of interlayer pairing in bilayer graphene

3. Exotic thermodynamics: Temperature-Induced condensation

4. Conclusion

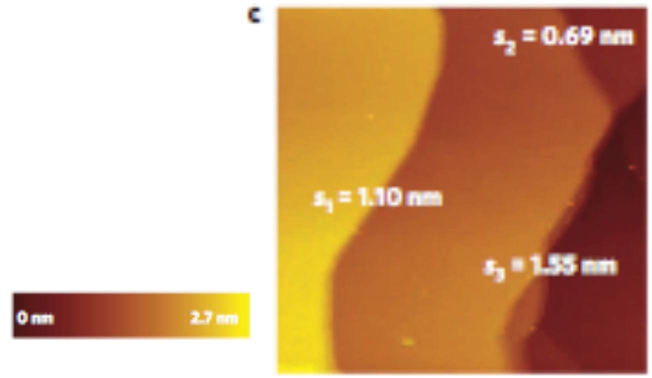
Proximity Induced Interlayer Superconductivity

Ti/Al (10/70nm) superconducting bilayer on top of graphene sheet



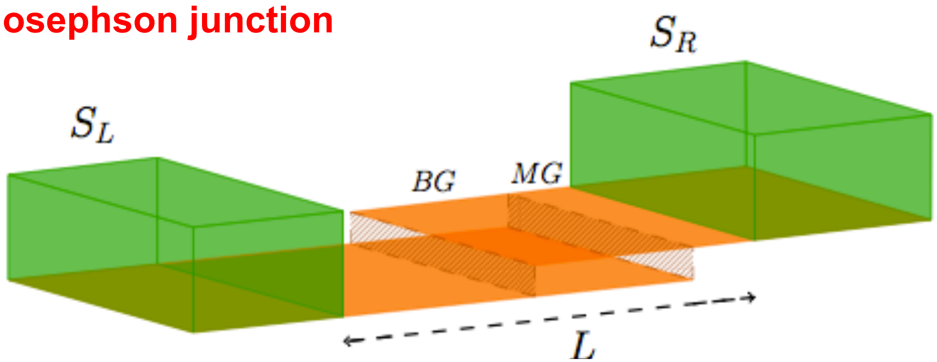
[Heersche et al, Nature (2007)]

Monolayer-Bilayer Step Structures



[Shuai-Hua Ji et al, Nature Materials (2011)]

Graphene Step Josephson junction



[B. Z. Rameshti, MZ, (2013)]

Superconductivity in the intercalated graphite compounds C_6Yb and C_6Ca

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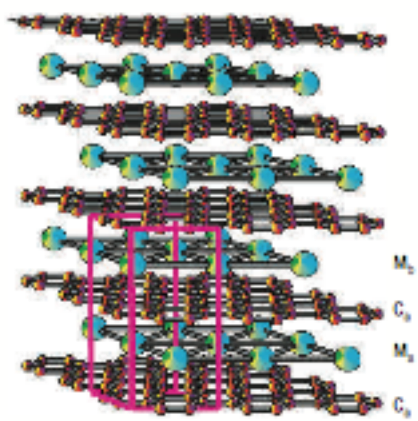

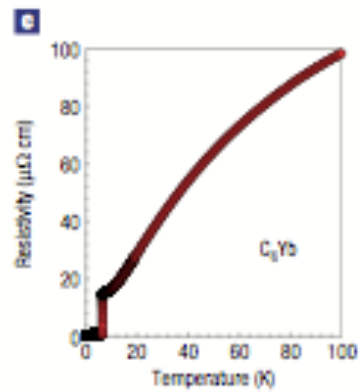

Ca intercalated bilayer graphene as a thinnest limit of superconducting C_6Ca

Kohei Kanetani[a], Katsuaki Sugawara[b,1], Takafumi Sato[a], Ryota Shimizu[b], Katsuya Iwaya[b], Taro Hitosugi[b], and Takashi Takahashi[a,b]

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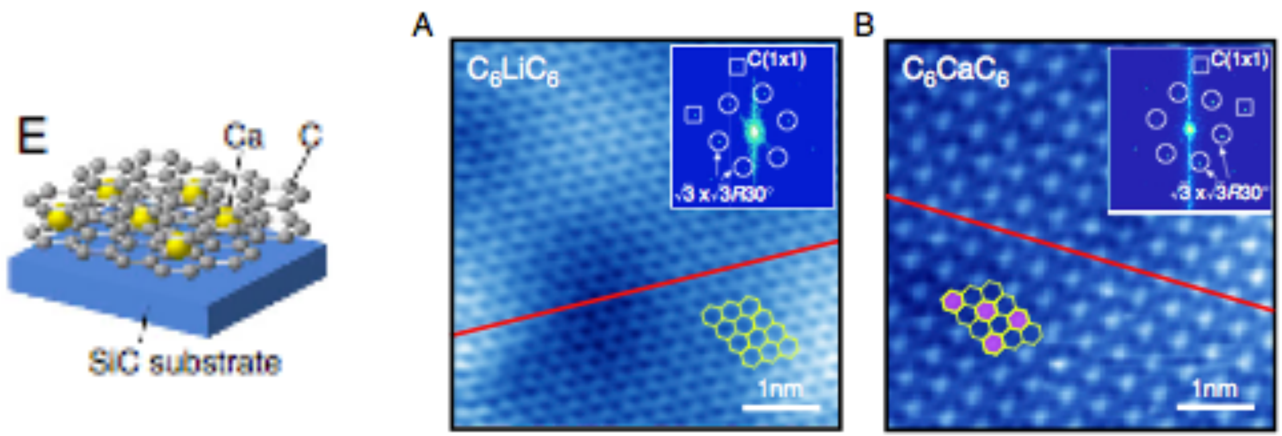
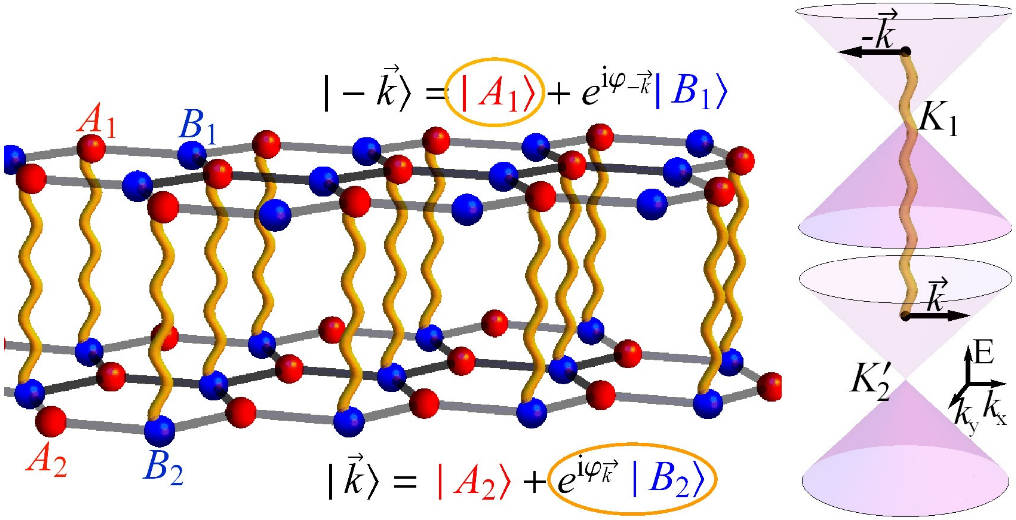


BCS Theory of Interlayer Superconductivity

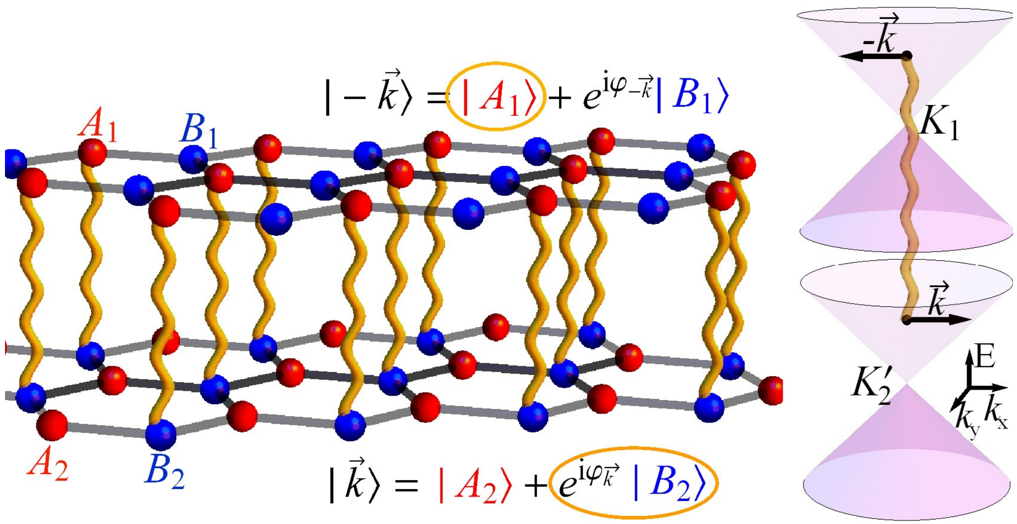
$$H_0 = -\mu \sum_{\ell,\sigma,i} n_{\ell,i,\sigma} - t \sum_{\ell,\sigma,\langle i,j \rangle} (a^{\dagger}_{\ell,i,\sigma} b_{\ell,j,\sigma} + \mathrm{H.c.}) - t_{\perp} \sum_{i,\sigma} (a^{\dagger}_{1,i,\sigma} b_{2,i,\sigma} + \mathrm{H.c.}),$$

$$V_{\perp} = -g_{\perp} \sum_{i} \sum_{\sigma,\sigma'} a^{\dagger}_{1,i,\sigma} a_{1,i,\sigma} b^{\dagger}_{2,i,\sigma'} b_{2,i,\sigma'},$$



[M. V. Hosseini, MZ, Phys. Rev. Lett (2012), Phys. Rev. B (2012)]

Symmetry of the Order Parameter



$$\Delta_{i,\perp} = -g_\perp \langle a_{1,i,\downarrow} b_{2,i,\uparrow} + a_{1,i,\uparrow} b_{2,i,\downarrow} \rangle,$$

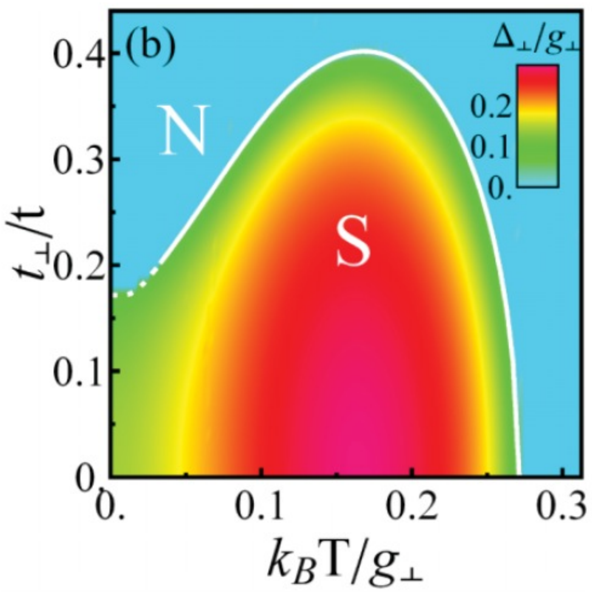
Local pairing interaction:
orbital part s-wave (symmetric)

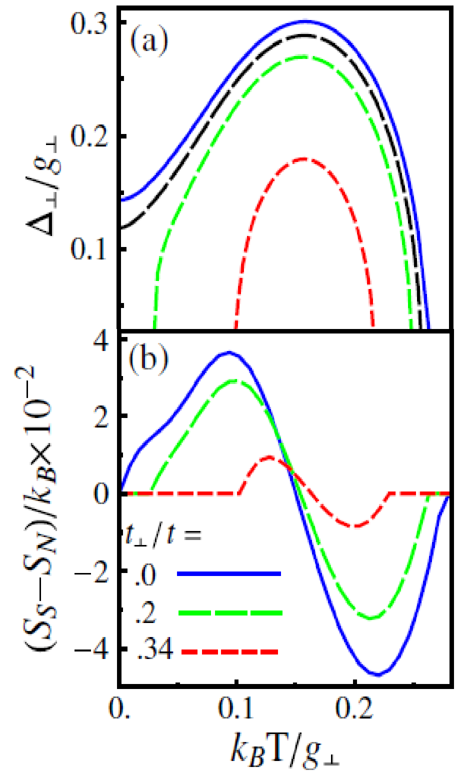
Bernal Stacking:
Pseudospin part is anti-symmetric

Pauli exclusion principle:
⇒ ***Spin-Triplet State***

Pair wave function:
s-wave Spin-Triplet state

Partial pairing: exotic thermodynamics





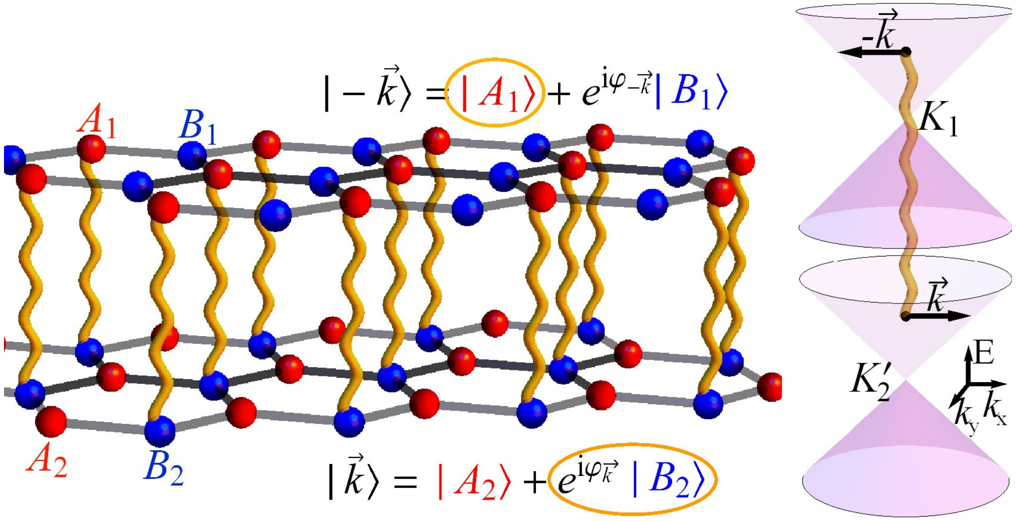
Temperature-induced condensation

Entropy of S (ordered) state can be higher than the N (less ordered) state!

[M. V. Hosseini, MZ, Phys. Rev. Lett (2012)]

Partial pairing due to Bernal Stacking

Starting from a partially paired state at low temperature: : thermal excitation can redistribute unpaired electrons in the states with partially pairing

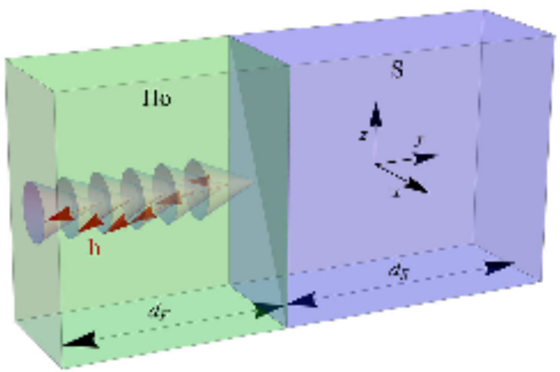


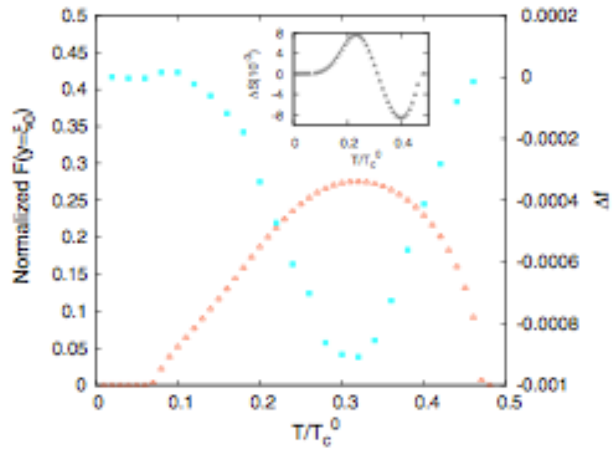
Partial pairing: exotic thermodynamics

PRL 108, 117005 (2012) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2012

Reentrant Superconducting Phase in Conical-Ferromagnet–Superconductor Nanostructures

Chien-Te Wu,[1,*] Oriol T. Valls,[1,†] and Klaus Halterman[2,‡]





Conclusion

- **Interlayer pairing of chiral electrons in graphene matterials:**

Relativistic quantum mechanical nature of electrons:

-temperature induced condensation (pairing)
-Step monolayer-bilayer proximity systems