V Escuela de Superconductividad

México, 27 noviembre 2021

Superconductividad en el MgB_2: a 20 años del descubrimiento

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Cinvestav-Mérida, México

Cinvestav
60 years

Funding: Conacyt-México
Grant No. 83604

Cinvestav

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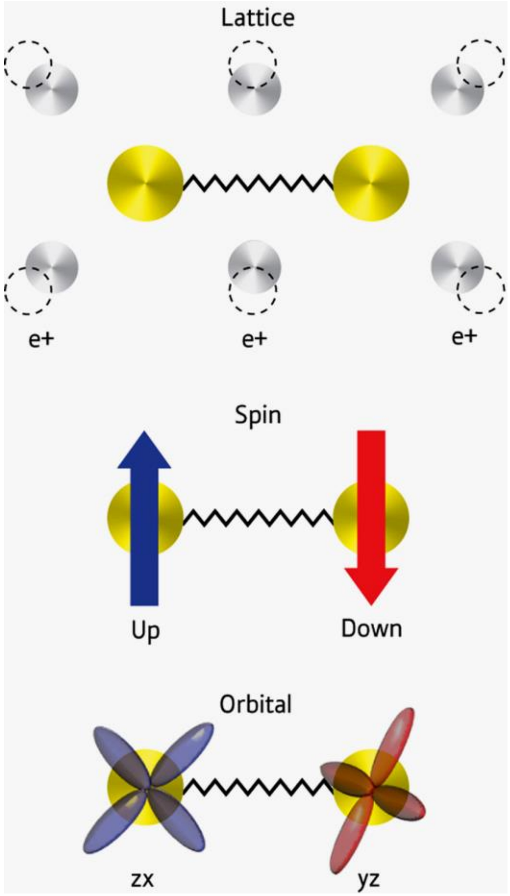
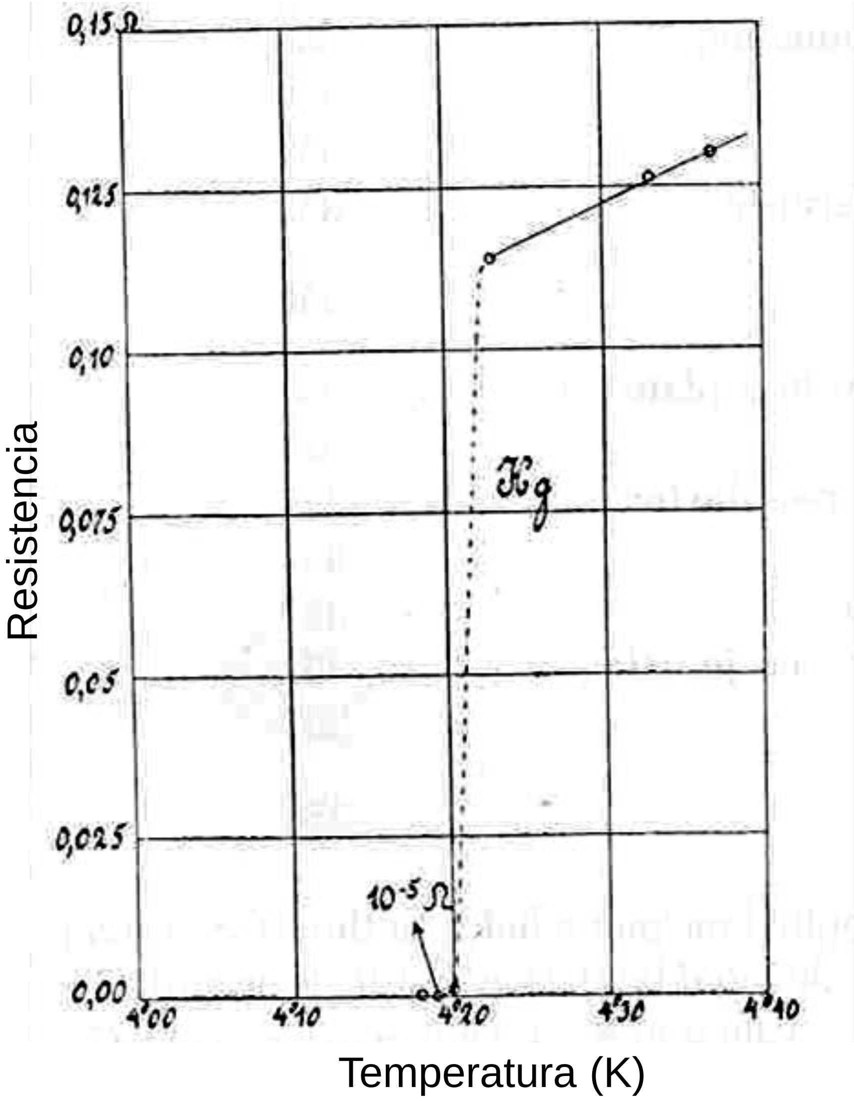


Descubrimiento de la superconductividad (1911)

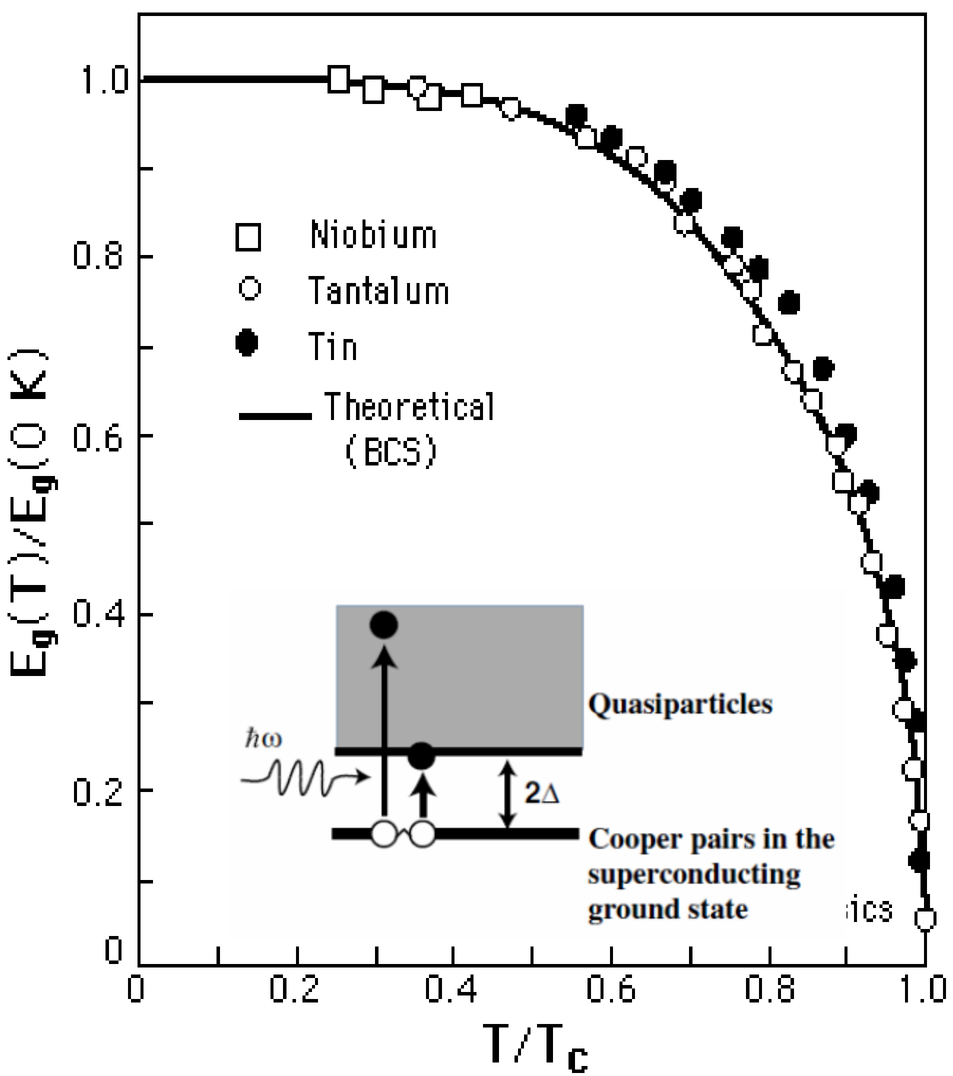
En 1911 Kamerling Onnes descubre que a la temperatura de 4.2 K el mercurio (Hg) pierde su resistencia eléctrica, a este fenómeno se denominó **superconductividad**.

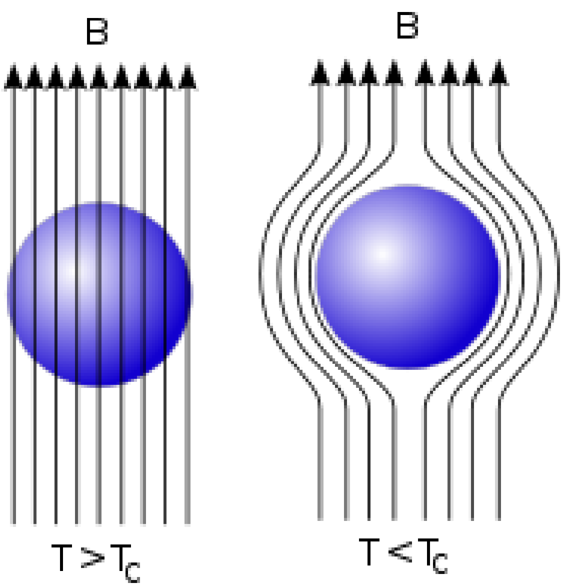
Un material superconductor es mucho mas que un conductor perfecto.

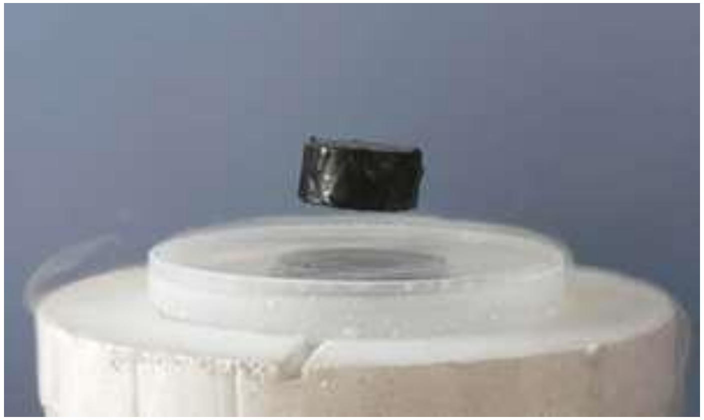
Resistencia eléctrica nula!!!



Brecha superconductora y Effecto Meissner

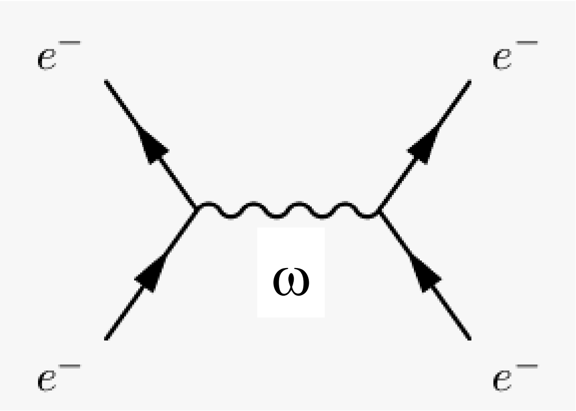






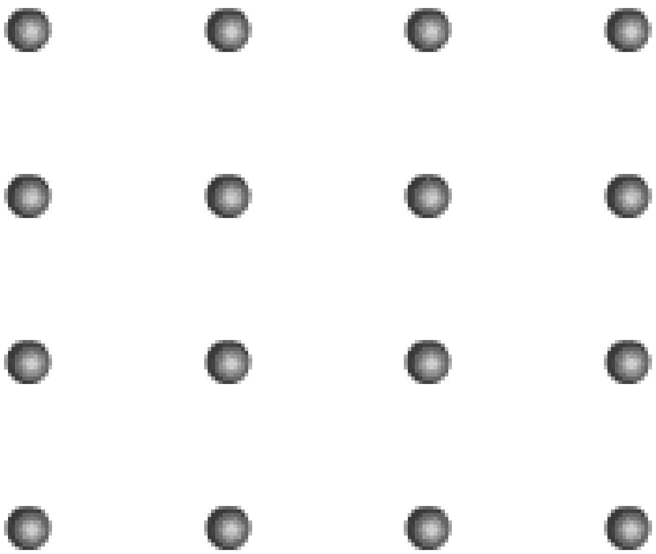
BCS Theory: electron-phonon interaction (1957)

BCS: Bardeen, Cooper and Schrieffer



The Nobel Prize in Physics 1972
John Bardeen, Leon N. Cooper, Robert Schrieffer

The first widely-accepted theoretical understanding of superconductivity was advanced in 1957 by American physicists John Bardeen, Leon Cooper, and John Schrieffer (above). Their ***Theories of Superconductivity*** became know as the BCS Theory.



https://www.nobelprize.org

John Bardeen - Nobel Lecture 1972

ELECTRON-PHONON INTERACTIONS AND SUPERCONDUCTIVITY

Nobel Lecture, December 11, 1972

By JOHN BARDEEN

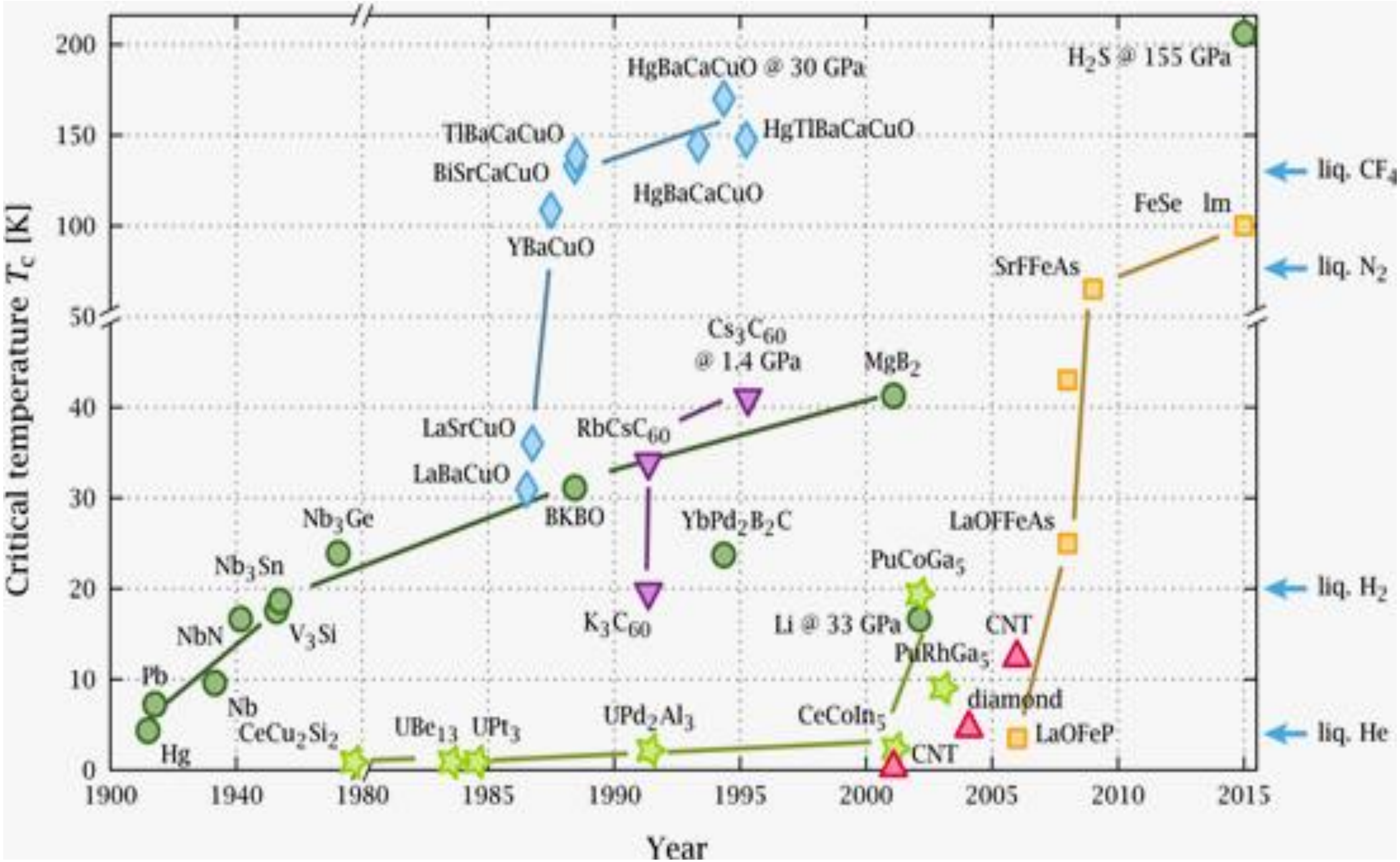
CONCLUSIONS

In this talk we have traced how our understanding of the role of **electron-**phonon interactions in superconductivity has developed from a concept to a precise quantitative theory. ....

All evidence indicates that the electron-phonon interaction is the dominant mechanism in the cases studied so far, which include many simple metals, transition metals, a rare earth, and various alloys and compounds. Except possibly for the metallic form of hydrogen, [35] which is presumed to exist at very high pressures, it is unlikely that the phonon mechanism will yield substantially higher transition temperatures than the present maximum of about 21 K for a compound of Nb, Al and Ge.

https://www.nobelprize.org/nobel_prizes/physics/laureates/1972/bardeen-lecture.html

Introduction: superconducting materials and Tc



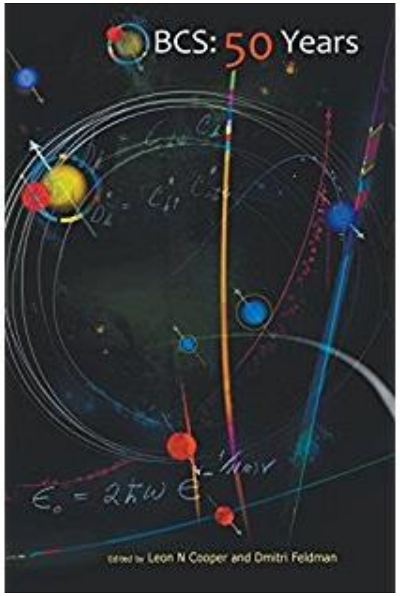
Introduction: Classes of Superconductors

1. **BCS or Conventional**: Electron pairing induced by electron-phonon interactions. Experiments explained.

   Materials: conventional metals, C60, some organics, doped semiconductors, MgB_2, hydrides ….

2. **Exotic or Unconventional**: Many theories on the electron pairing, but no concensus on the mechanism.

   Materials: cooper oxides, heavy fermion metals, some organics, dicalcogenides, (Fe,Ni) oxypnictides, FeSe, ….



M.L. Cohen, "BCS: 50 years" (World Scientific, 2010), pag. 375.

Descrubrimiento de SC en el MgB_2

Superconductivity at 39 K in magnesium diboride

Jun Nagamatsu*, Norimasa Nakagawa*, Takahiro Muranaka*, Yuji Zenitani* & Jun Akimitsu*†

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† *CREST, Japan Science and Technology Corporation, Kawaguchi, Saitama 332-0012, Japan*

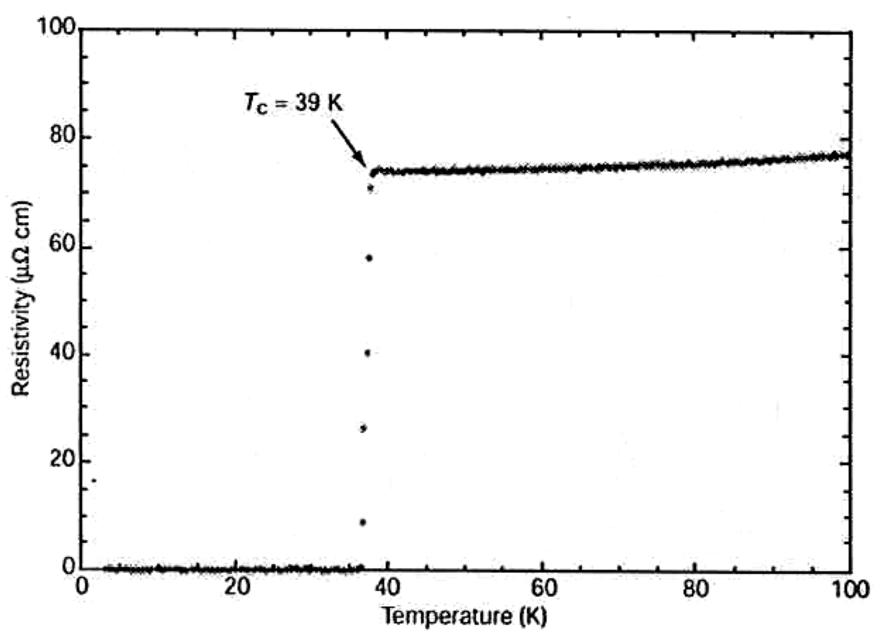
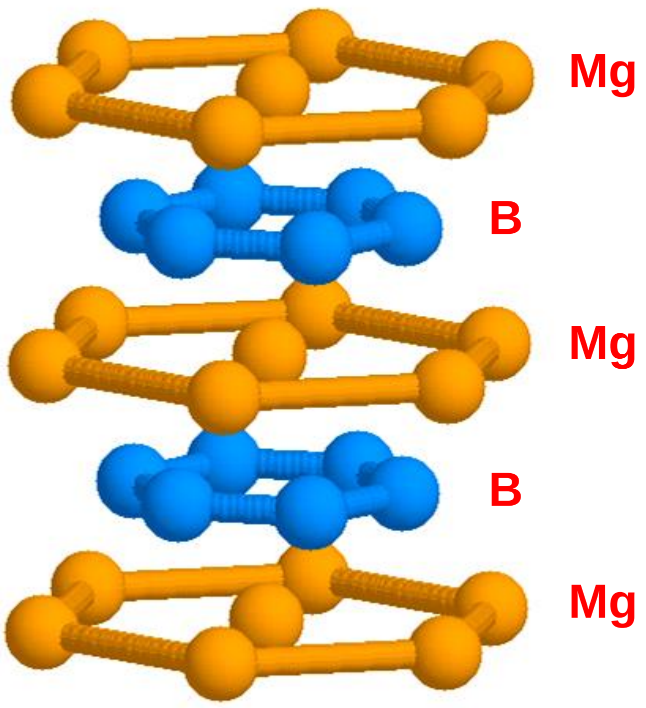


Figure 4 Temperature dependence of the resistivity of MgB_2 under zero magnetic field.

Nature **40**, 63 (1 march 2001).



Crystal Structure of MgB_2
Space group P6/mmm (no. 191)
AlB_2 (omega phase)

MgB_2: magnesium diboride

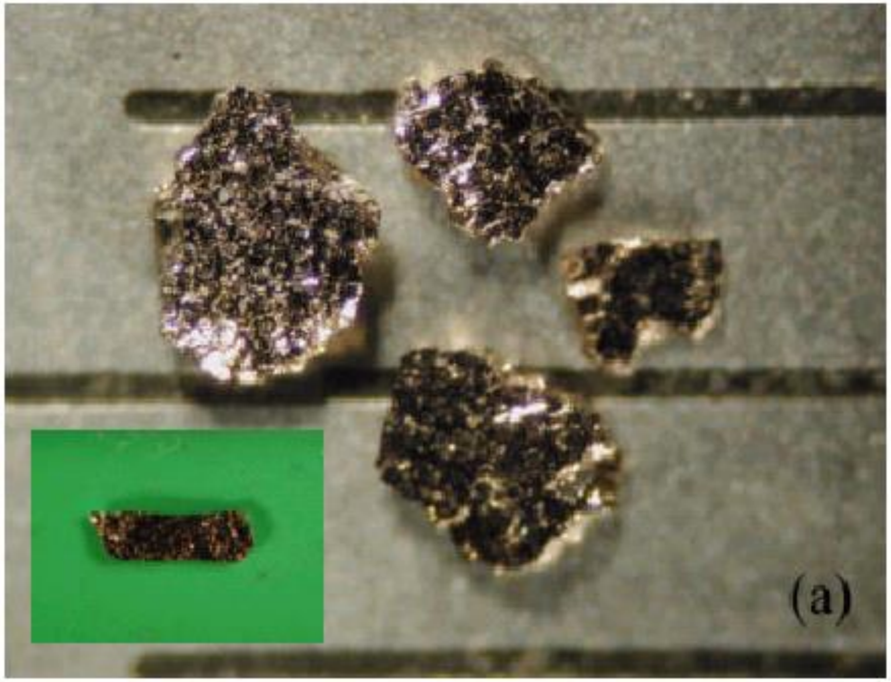
The compound MgB_2 has been kown since 1953 !!!

Samples: crystals of Al and C-doped MgB_2

$Mg_{1-x}Al_xB_2$

J. Karpinski et al.,
Cond-mat/ 0304658 (2003).

$MgB_{2-x}C_x$



S. Lee et al.,
Cond-mat/ 0305485 (2003).

MgB$_2$: electronic and vibrational properties

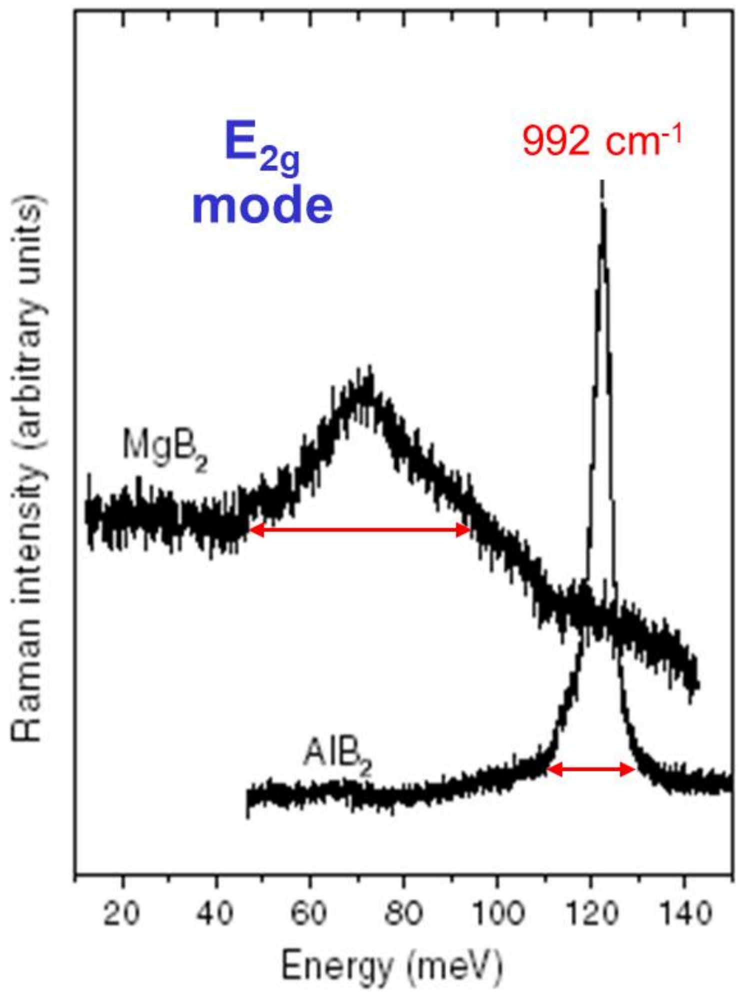
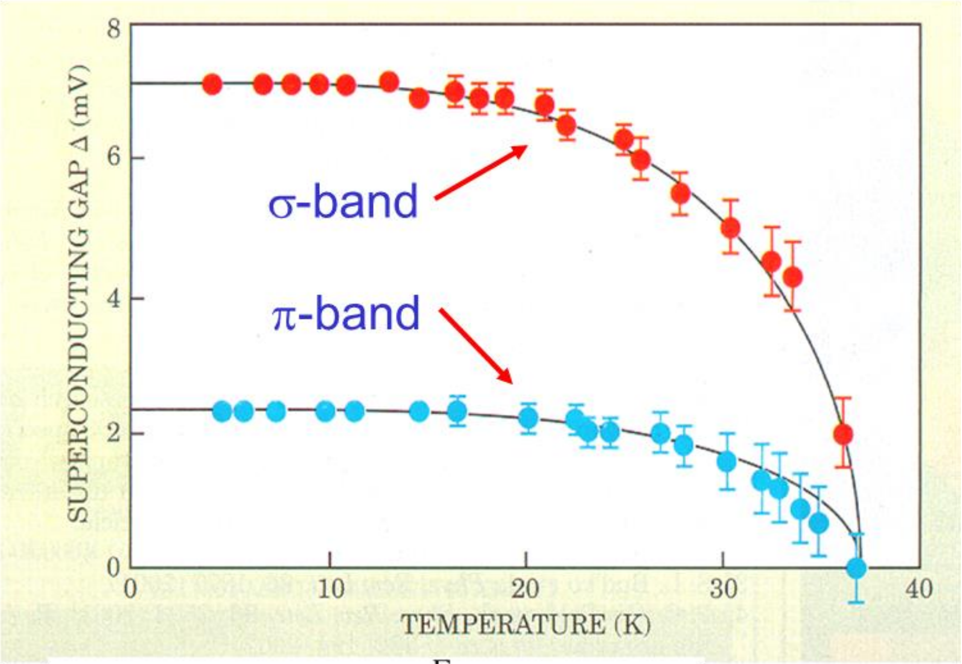
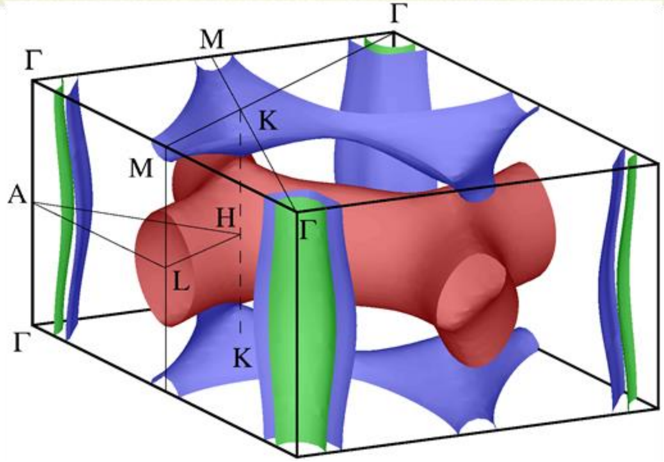


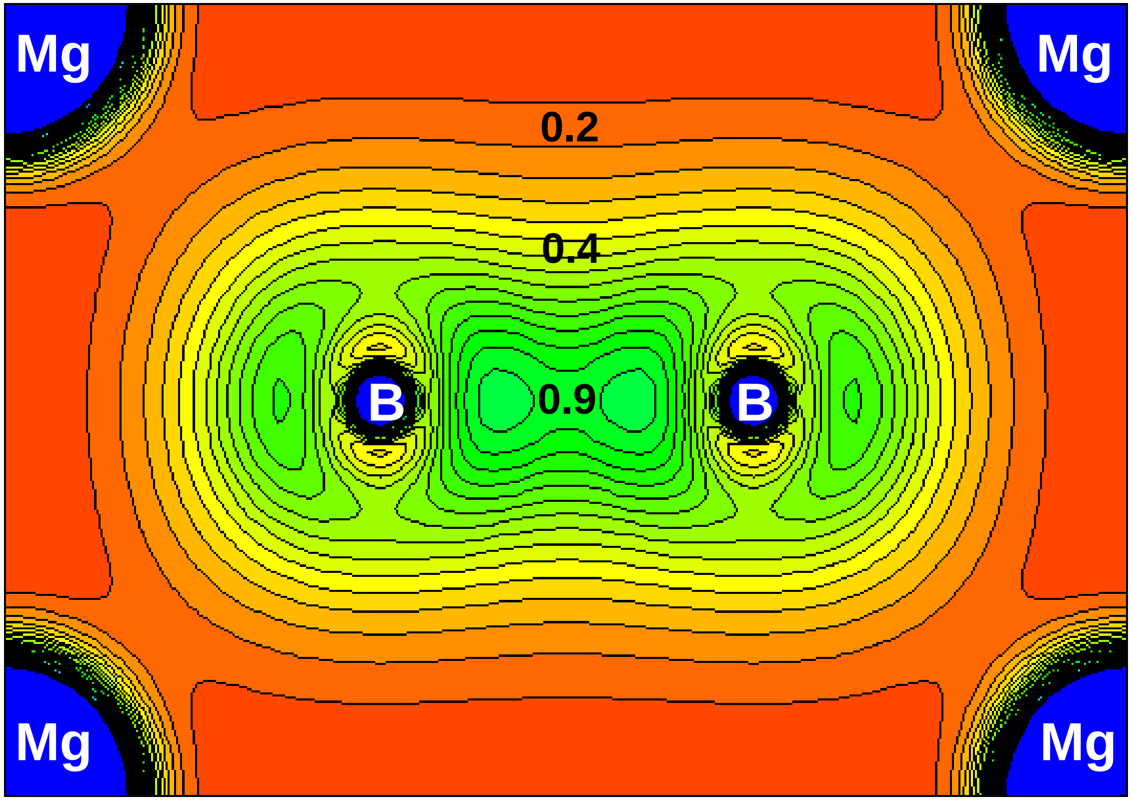
FIG. 1. Micro-Raman spectra obtained from polycrystalline grains of MgB$_2$ and AlB$_2$ at room temperature (λ = 514.5 nm).



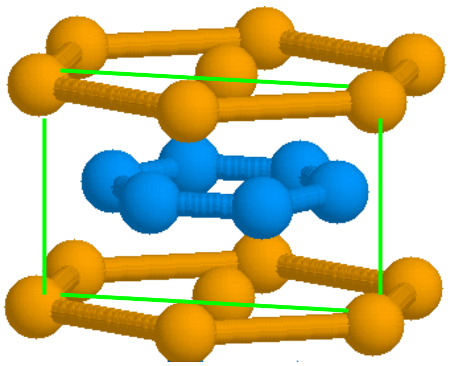


Fermi Surface

MgB_2: enlace químico



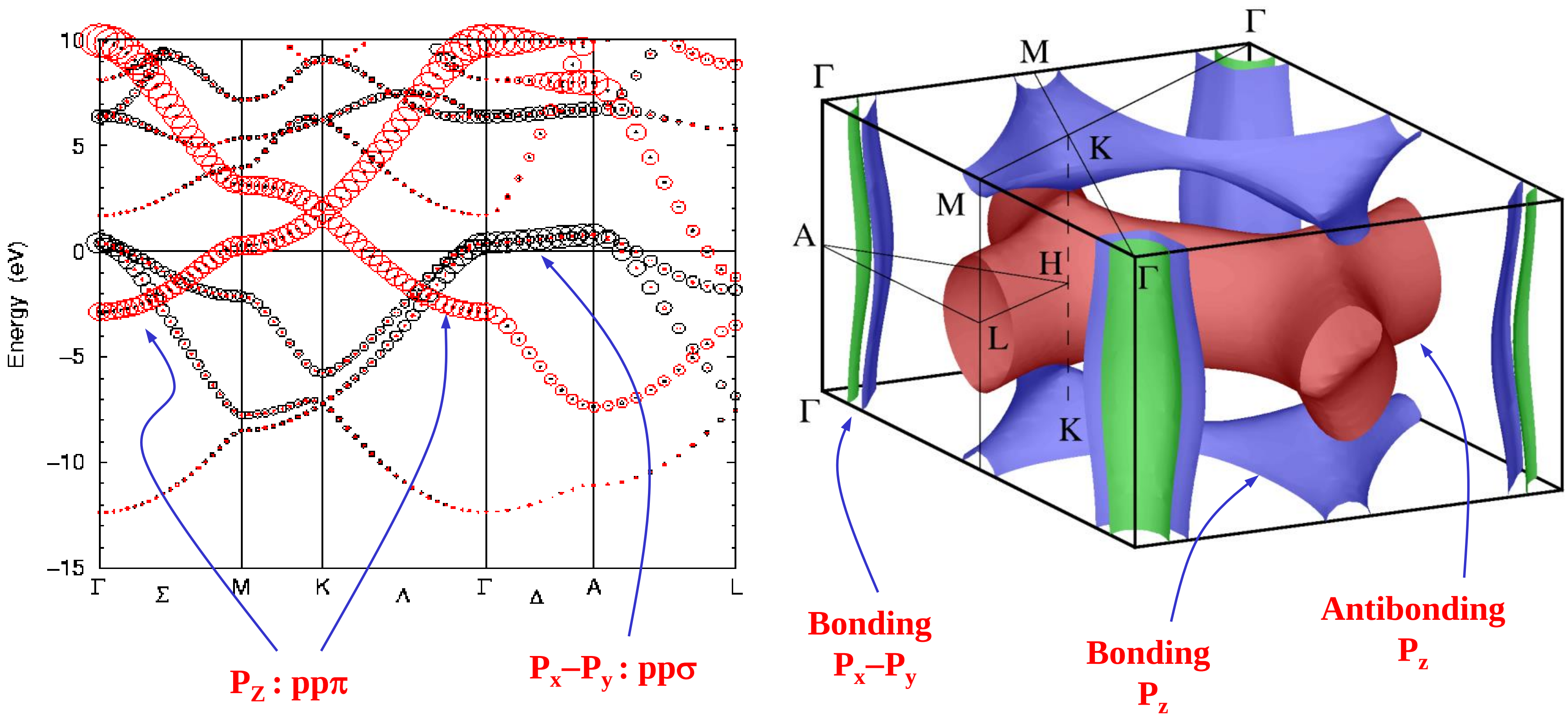
A. Aguayo and R. de Coss (april 2001)
Cinvestav-Mérida, México.



$\Delta\rho=0.05\ e/Å^3$

MgB_2: estructura electrónica

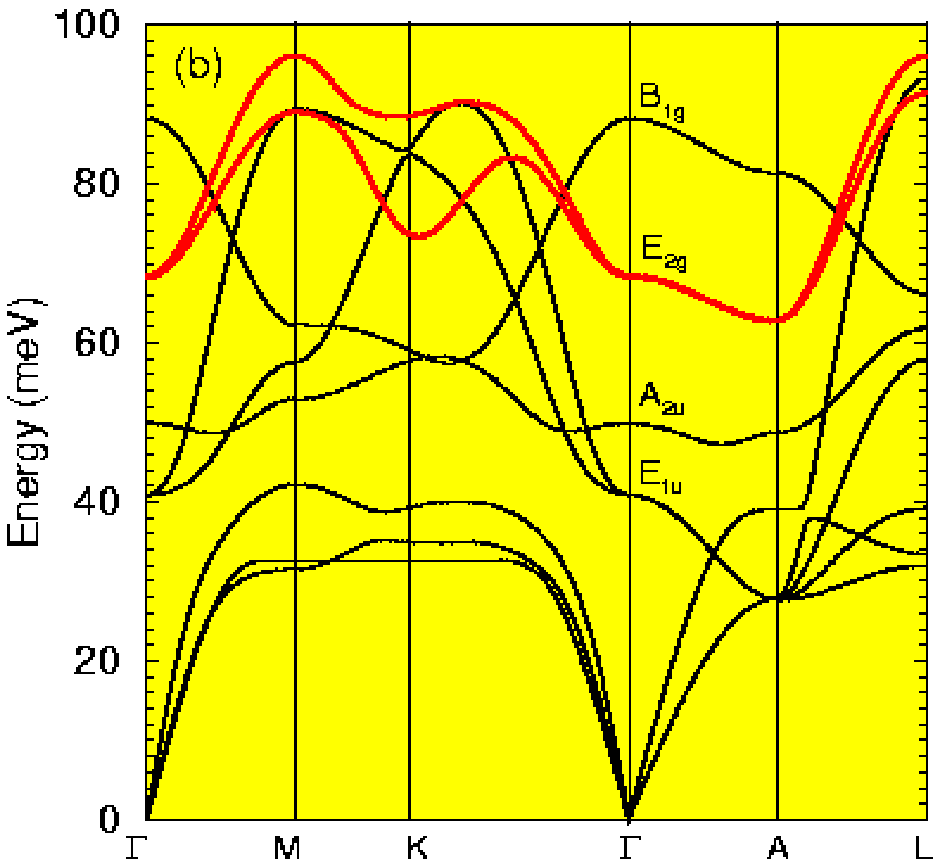
Band structure and Fermi surface of MgB_2 (FP-LAPW)

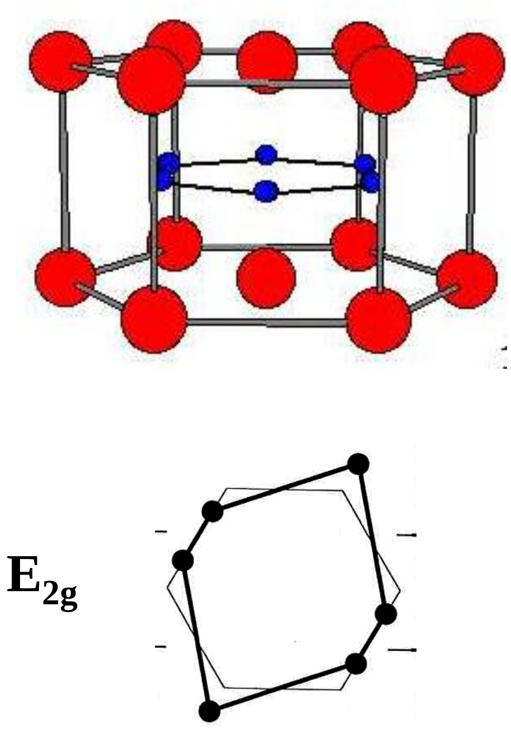


L. Kortus et al. *Phys. Rev. Lett.* **86**, 4656 (2001).

MgB_2: propiedades vibracionales

Estructura de bandas fonónicas calculadas: pseudopotenciales.

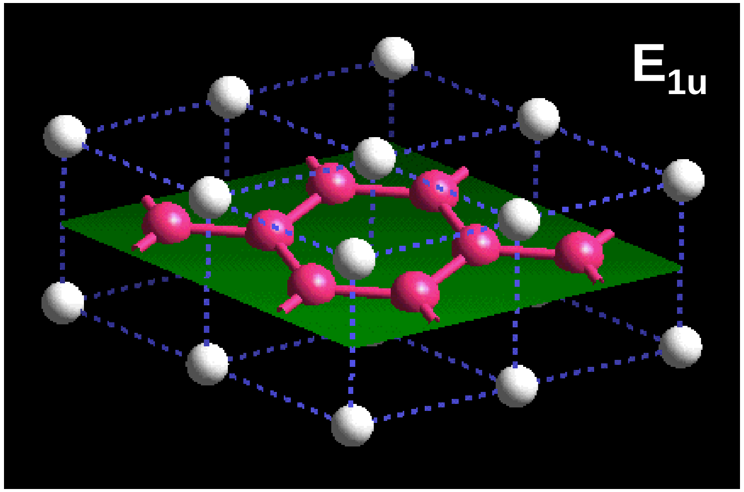


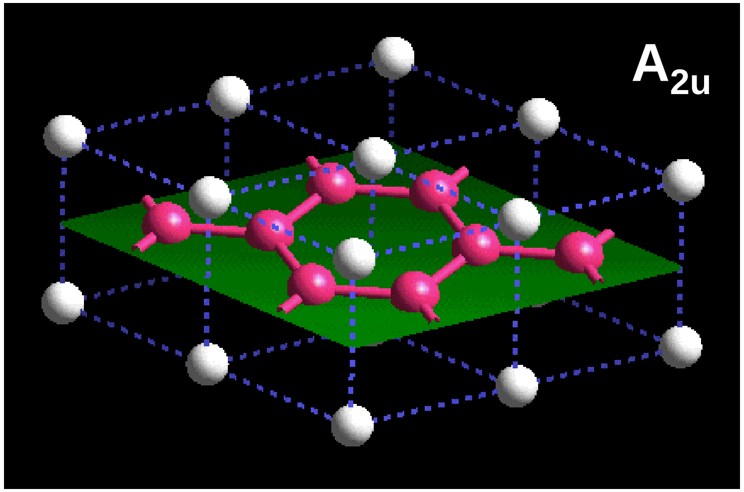


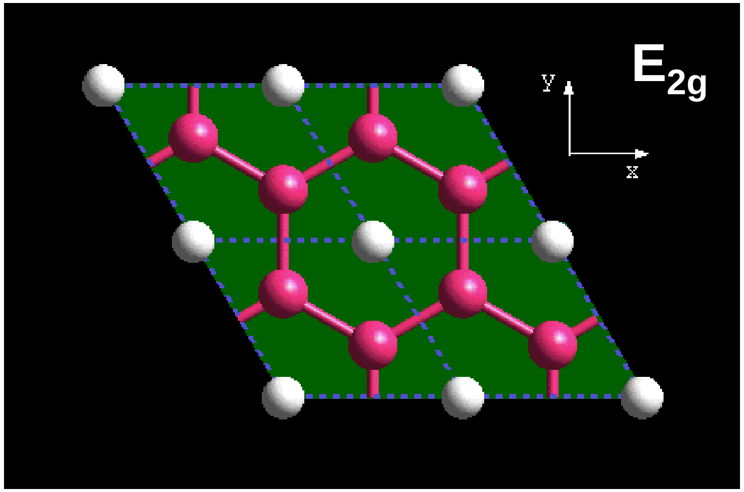
Planos de boro

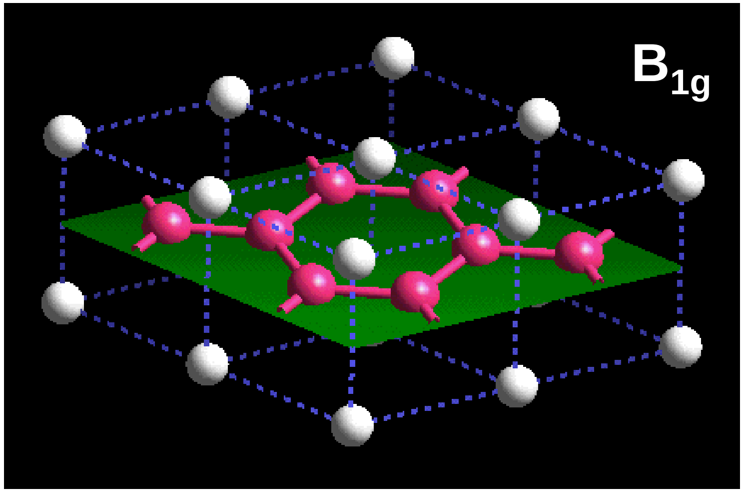
T. Yildirim et al., Phys. Rev. Lett. **87**, 37001 (2001).

MgB_2: modos vibracionales



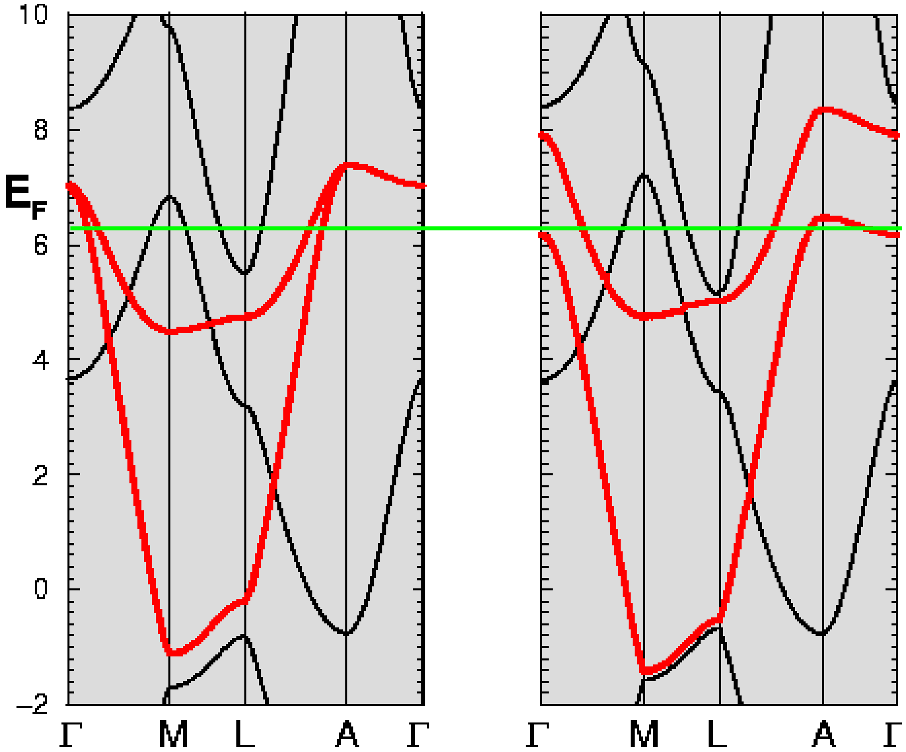




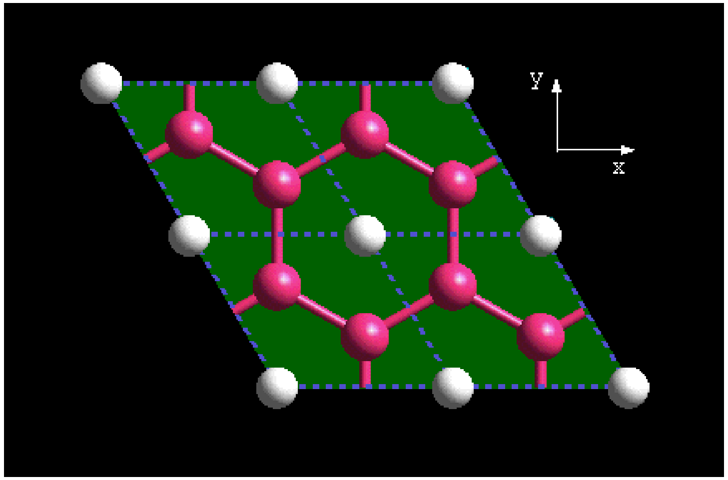


MgB_2: acoplamiento e-ph

Acoplamiento del modo E_{2g} con las bandas p_x-p_y

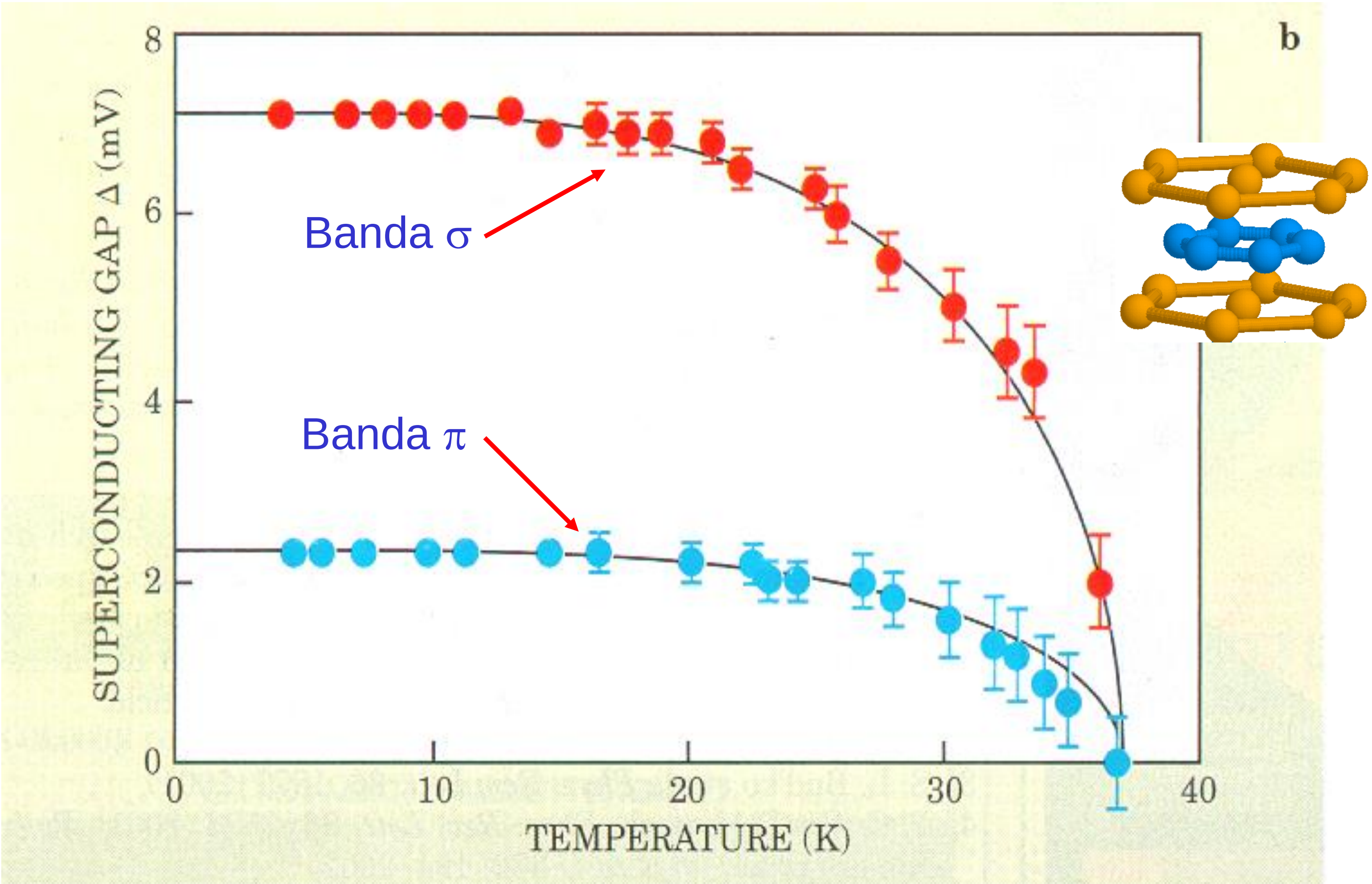


Modo E_{2g}



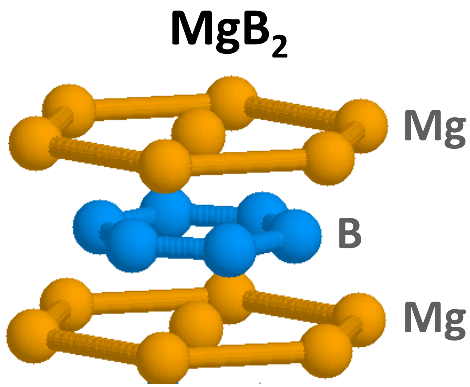
T. Yildirim et al., Phys. Rev. Lett. 87, 37001 (2001).
Home Page: http://www.ncnr.nist.gov/staff/taner/mgb2/

MgB_2: dos brechas superconductoras!!!

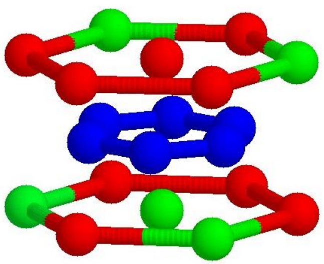


P.C. Canfield and G.W. Crabtree. *Physics Today* **56**, 34 (2003).

Our contributions: MgB_2 superconducting alloys



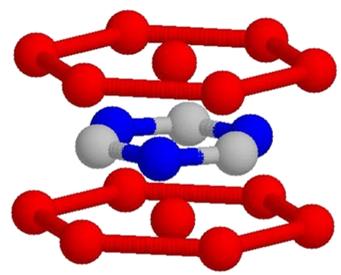
- Physical Review B **66**, 012511 (2002).
- Physical Review B **79**, 134523 (2009).
- Physical Review B **81**, 054519 (2010).
- Physical Review B **82**, 224508 (2010).
- Physics Proceedia **36**, 479 (2012).



$Mg_{1-x}Al_xB_2$

Z_{Mg}=12 and Z_{Al}=13

Z_B=5



$MgB_{2-x}C_x$

Z_{Mg}=12

Z_B=5 and Z_C=6

✓ **MgB_2 doped with Al and C:** We found that Al- and C-doping reduce drastically the DOS at the Fermi level and induce a strong phonon renormalization, producing a drop of Tc. In particular, we predict the loss of superconductivity for x(Al)=0.56, which was confirmed by experiments.

Colaboradores

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Dr. Klaus-Peter Bohnen

Karlsruhe Institute of Technology

Germany

Science

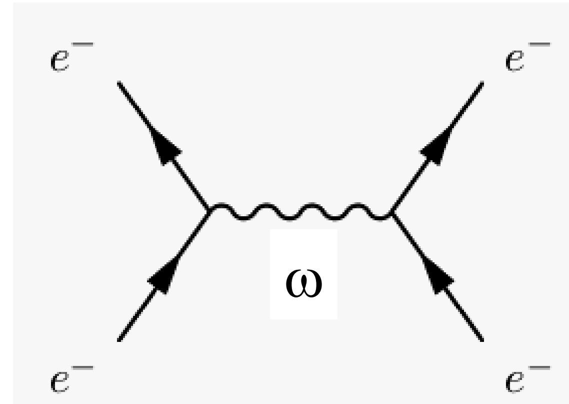
M.L. Cohen, Science **234**, 549 (1986)

Predicting New Solids and Superconductors

Función isotrópica de Eliashberg

$$\alpha^2 F(\omega) = \frac{1}{2\pi N(0)} \sum_{\mathbf{q}\lambda} \frac{\gamma_{\mathbf{q}\lambda}}{\omega_{\mathbf{q}\lambda}} \delta(\omega - \omega_{\mathbf{q}\lambda})$$

$\omega_{\mathbf{q}\lambda}$: frec. del modo fonónico ($\mathbf{q}\lambda$)



Ancho de línea del fonón

$$\gamma_{\mathbf{q}\lambda} = 2\pi\omega_{\mathbf{q}\lambda} \sum_{\mathbf{k}\nu\nu'} \left| g^{\mathbf{q}\lambda}_{\mathbf{k}+\mathbf{q}\nu',\mathbf{k}\nu} \right|^2 \delta(\epsilon_{\mathbf{k}\nu} - \epsilon_F)\delta(\epsilon_{\mathbf{k}+\mathbf{q}\nu'} - \epsilon_F)$$

Fórmula de Allen-Dynes: $T_c = \frac{\omega_{log}}{1.2} \exp\left(\frac{-1.04(1+\lambda)}{\lambda - \mu^*(1+0.62\lambda)} \right)$

donde $\lambda = 2 \int_0^\infty d\omega \frac{\alpha^2 F(\omega)}{\omega}$

$$\omega_{log} = \exp\left(\frac{2}{\lambda} \int_0^\infty d\omega \frac{\alpha^2 F(\omega)}{\omega} \ln(\omega) \right)$$

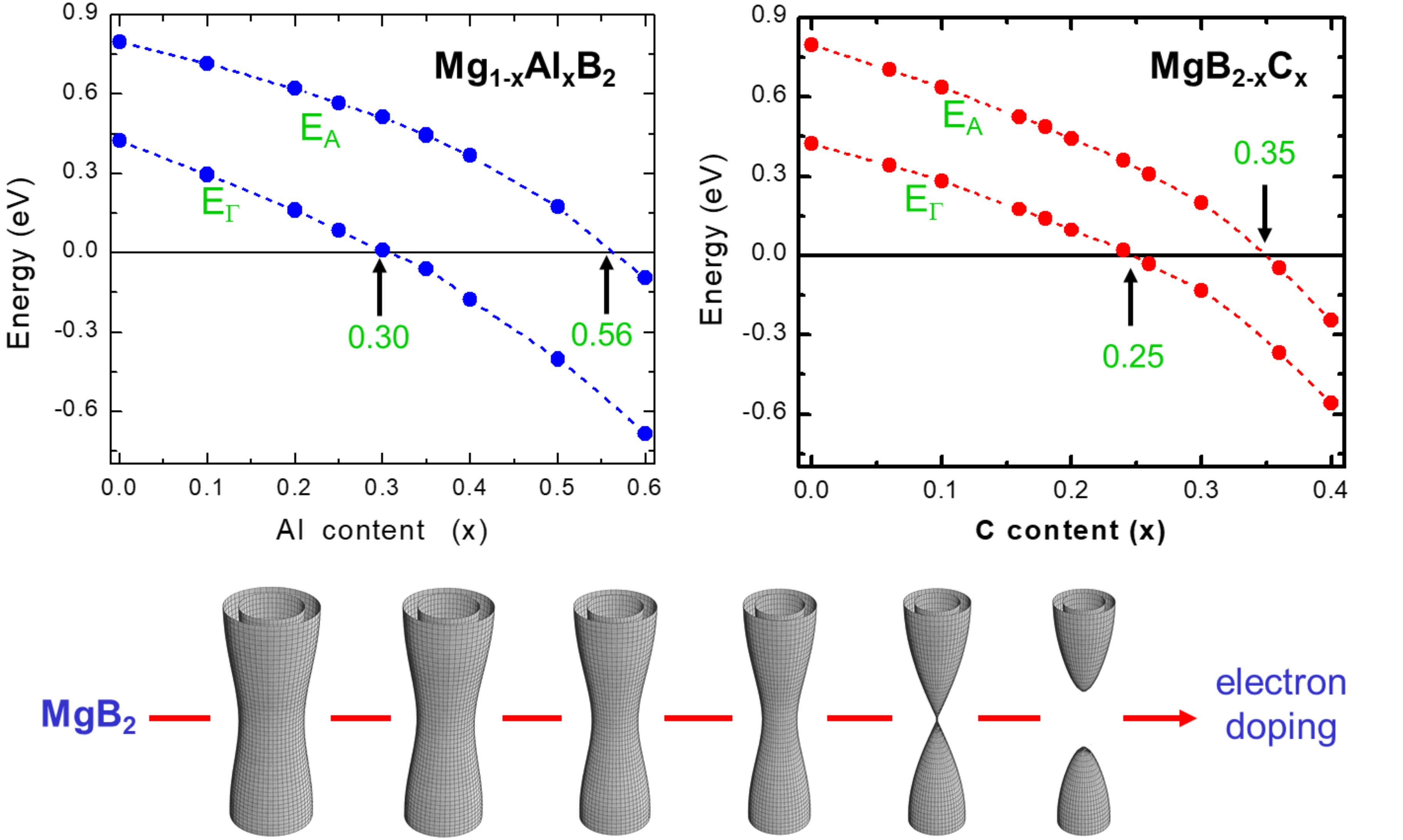
$N(0)$: DOS al nivel de Fermi

λ : constante de acoplamiento

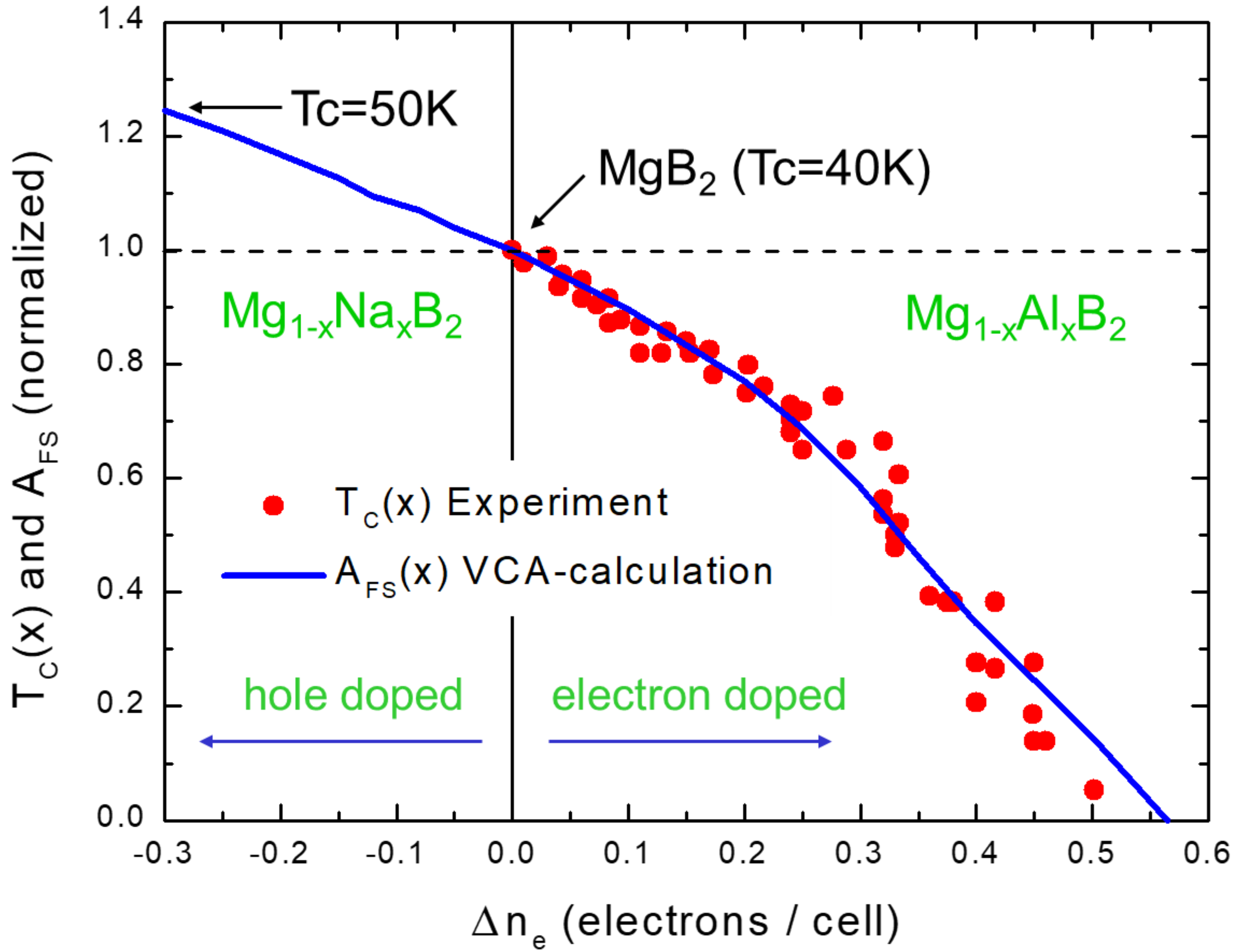
ω_{log} : frec. efectiva promedio

μ^* : inter. elec-elec apantallada

Fermi surface evolution of doped MgB_2



Fermi surface and Tc in doped MgB_2



PHYSICAL REVIEW B **79**, 134523 (2009)

Effects of Al and C doping on the electronic structure and phonon renormalization in MgB_2

O. De la Peña-Seaman,[1,2] R. de Coss,[1] R. Heid,[2] and K.-P. Bohnen[2]
[1]*Departamento de Física Aplicada, Centro de Investigación y de Estudios Avanzados del IPN, Apartado Postal 73 Cordemex 97310 Mérida, Yucatán, México*
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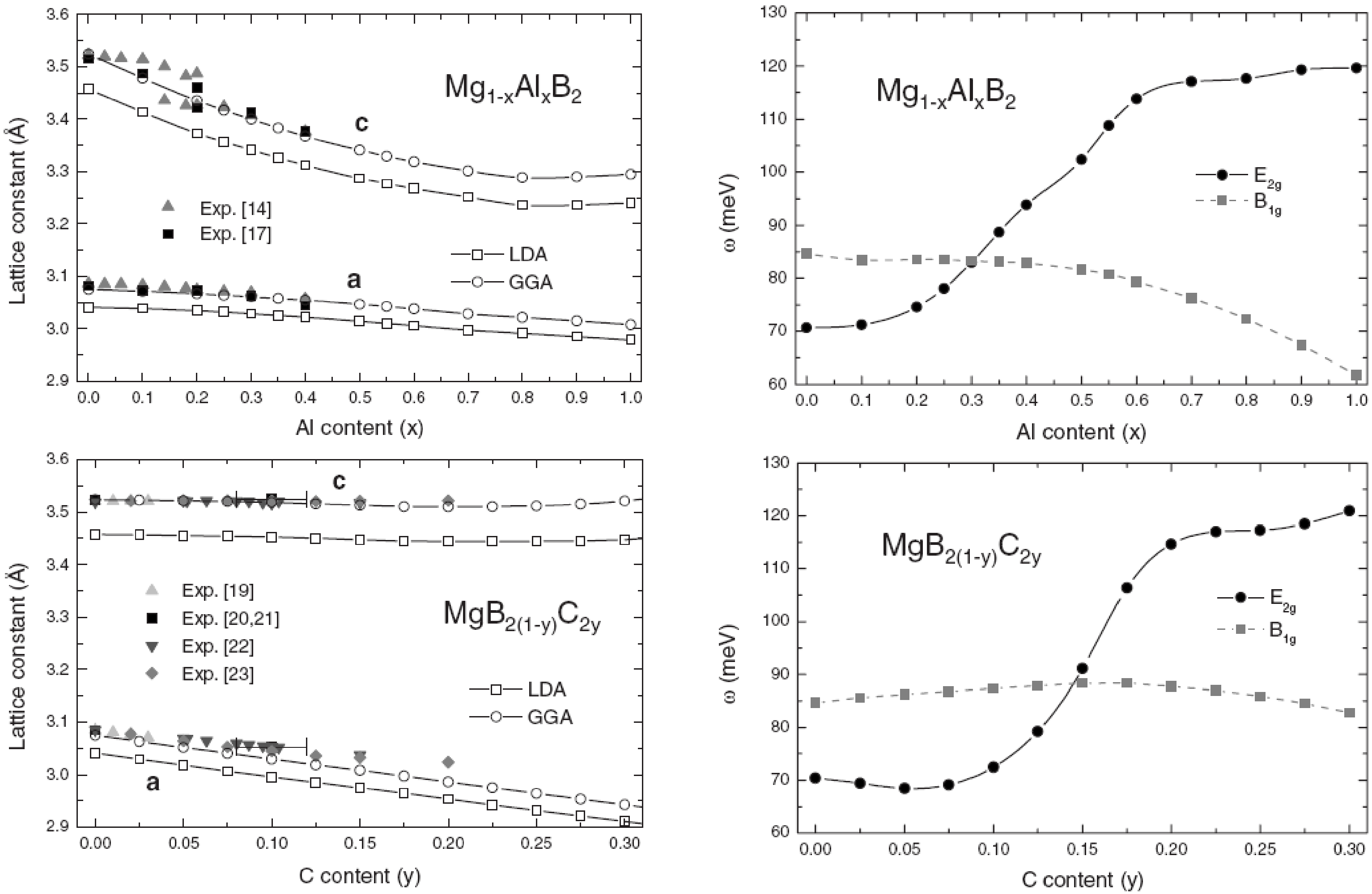
(Received 21 January 2009; revised manuscript received 10 March 2009; published 27 April 2009)



PHYSICAL REVIEW B **82**, 224508 (2010)

Electron-phonon coupling and two-band superconductivity of Al- and C-doped MgB_2

O. De la Peña-Seaman,[1,2] R. de Coss,[1] R. Heid,[2] and K.-P. Bohnen[2]

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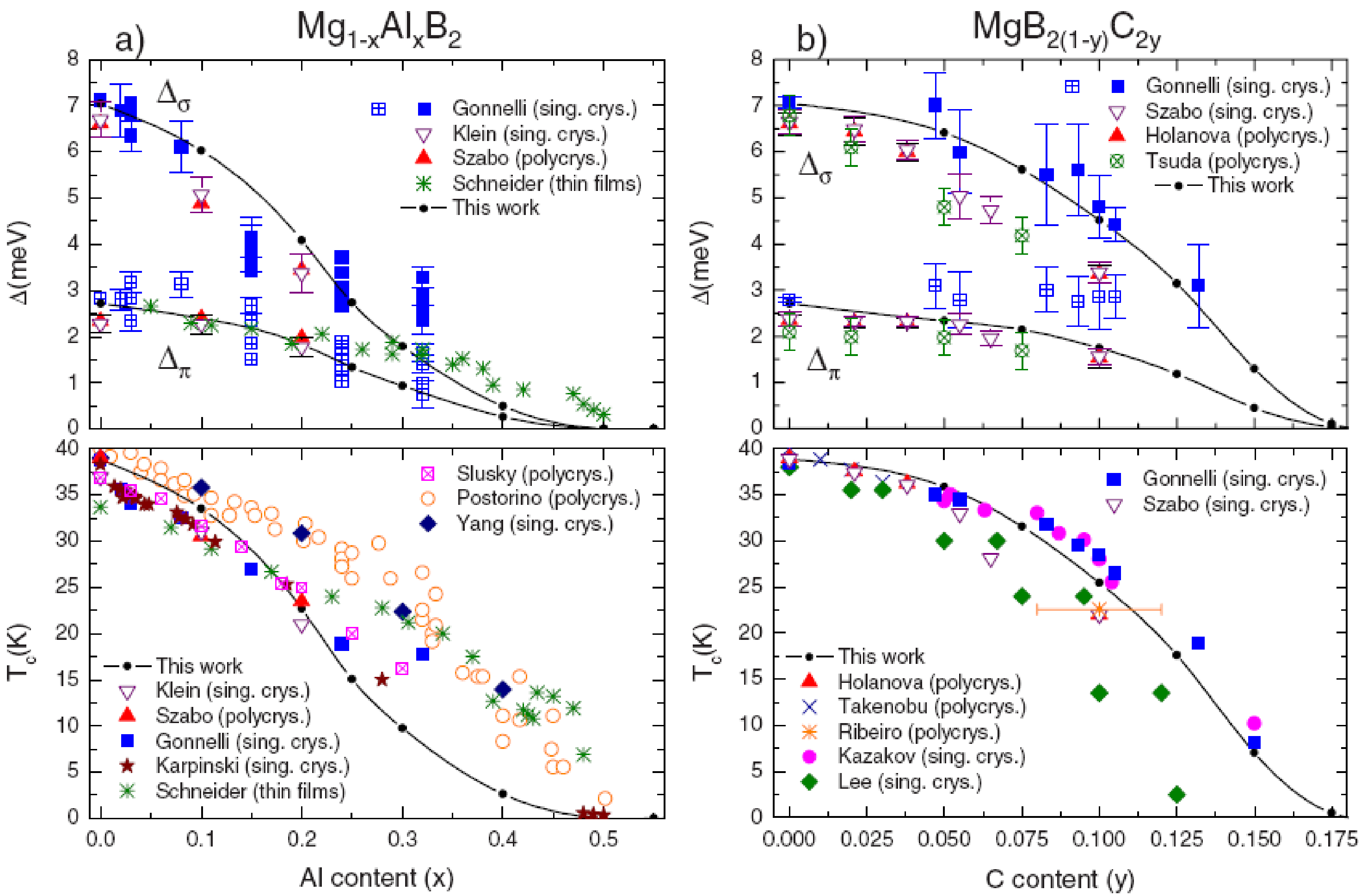

PHYSICAL REVIEW B **82**, 224508 (2010)

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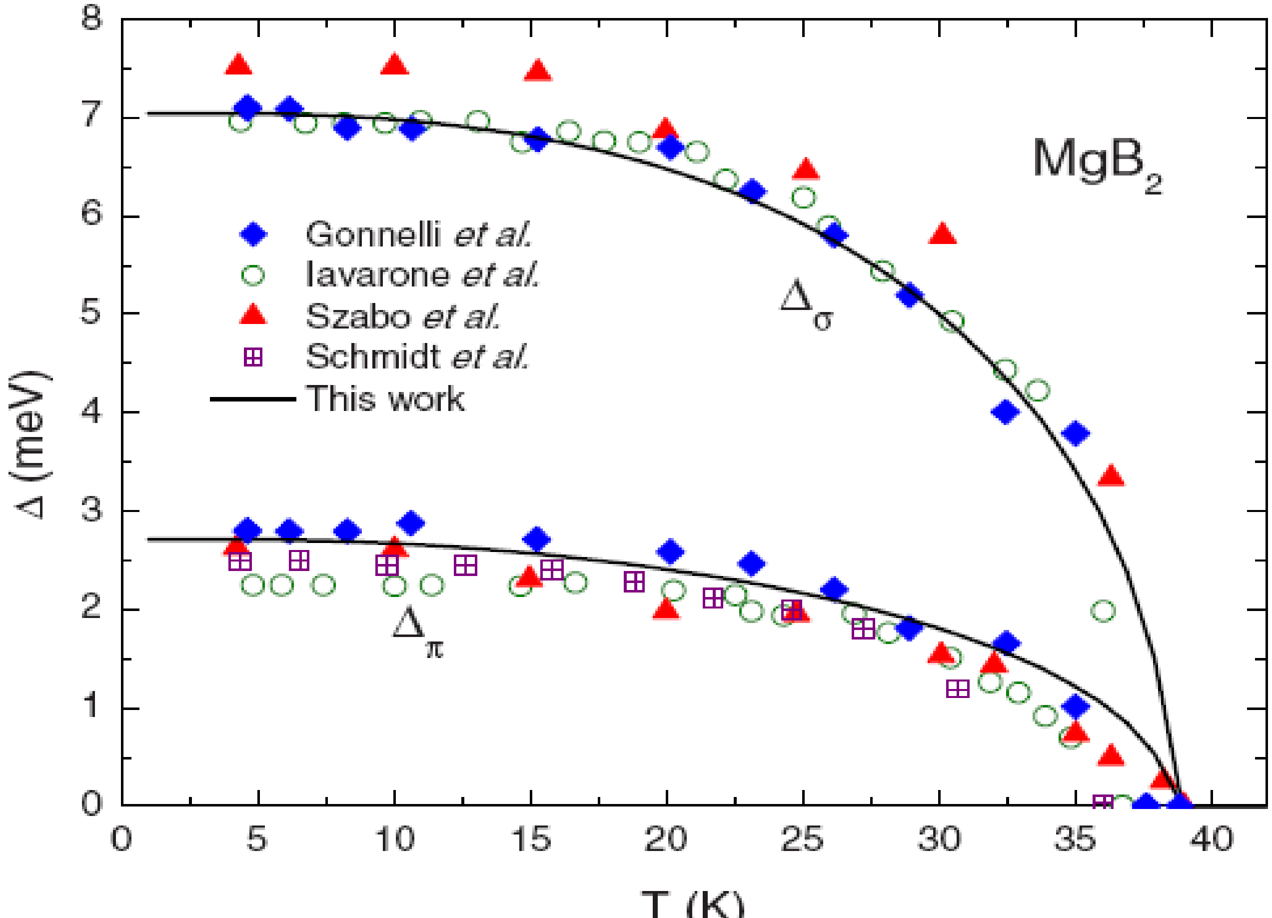
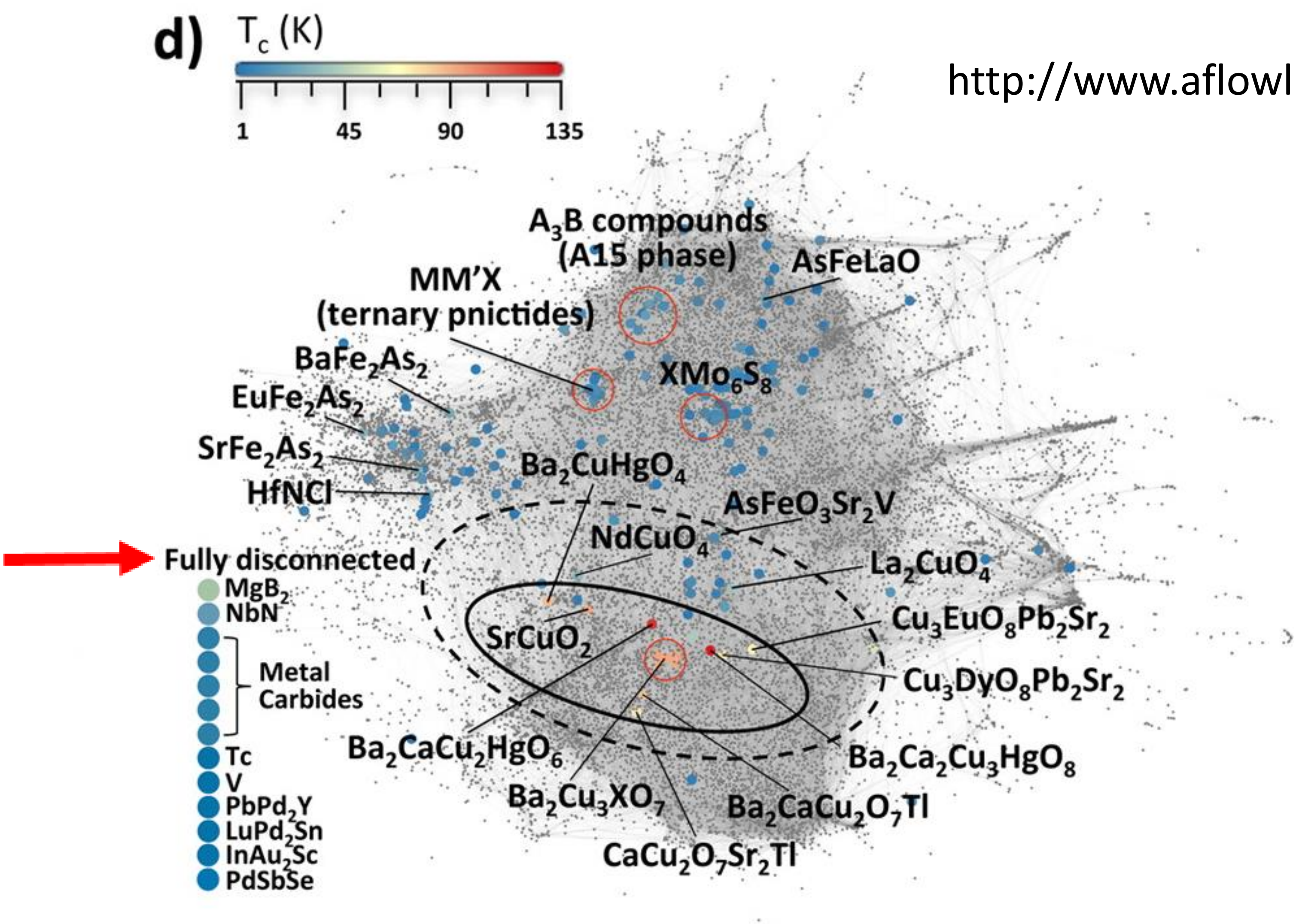


Familias de compuestos superconductores

http://www.aflowlib.org/

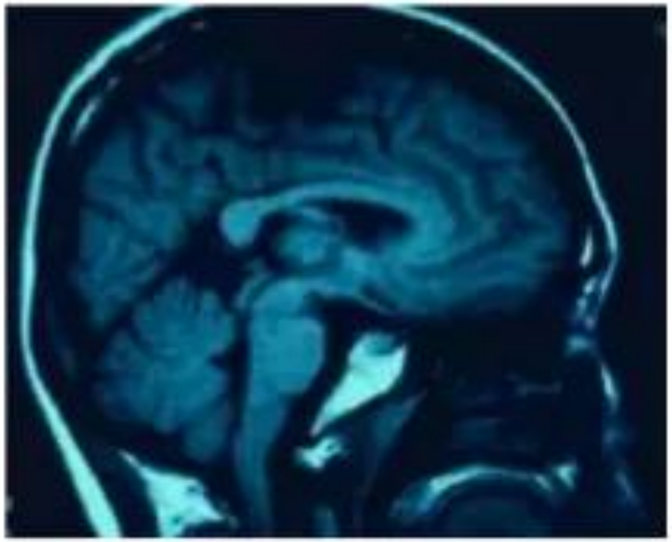


O. Isayev et al., Chem. Mater. **27**, 735 (2015)

Aplicaciones de la superconductividad

- •Particle Accelerators
- •Generators
- •Transportation
- •Power Transmission
- •Electric Motors
- •Military
- •Computing
- •Medical
- •B Field Detection (SQUIDS)

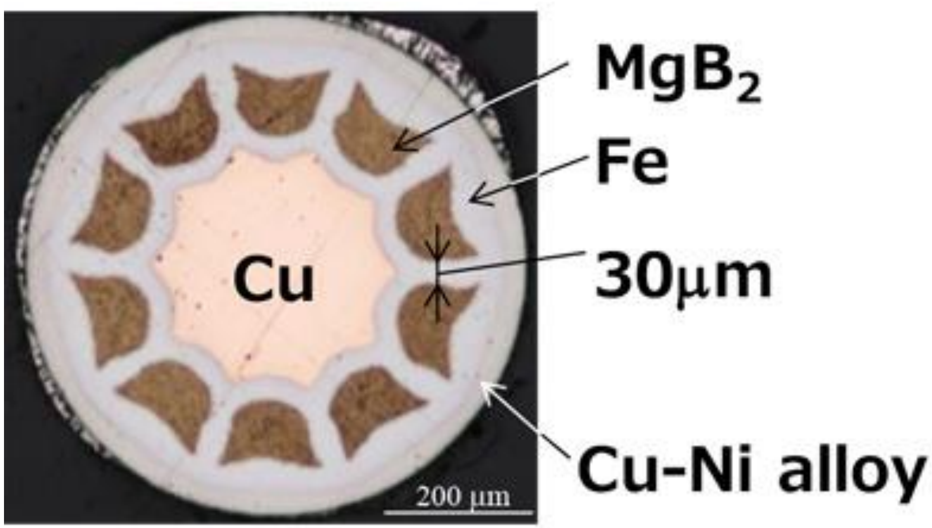
The Yamanashi MLX01 MagLev train



Cables superconductores de MgB_2

Development of 8-km-long Magnesium Diboride Superconducting Wire

Reduces Cooling Power of Superconducting Magnet by Half



Aplicaciones del MgB_2

ASG SUPERCONDUCTORS

MgB_2 OPENS THE DOOR TO HIGH PERFORMANCE MAGNET RAMPING

Energy Storage, intraoperative MRI and particle therapy applications: empirical evidence shows MgB_2 confirms all theoretical expectations in carrying rapidly varying currents at 20K.

Alessio Capelluto and Lorenzo Mauro
ASG Superconductors S.p.A., R&D division, Genova, Italy

ARPS experiments on monolayers of MgB_2

OPEN

Free surfaces recast superconductivity in few-monolayer MgB_2: Combined first-principles and ARPES demonstration

Scientific Reports **7**, 14458 (2017)

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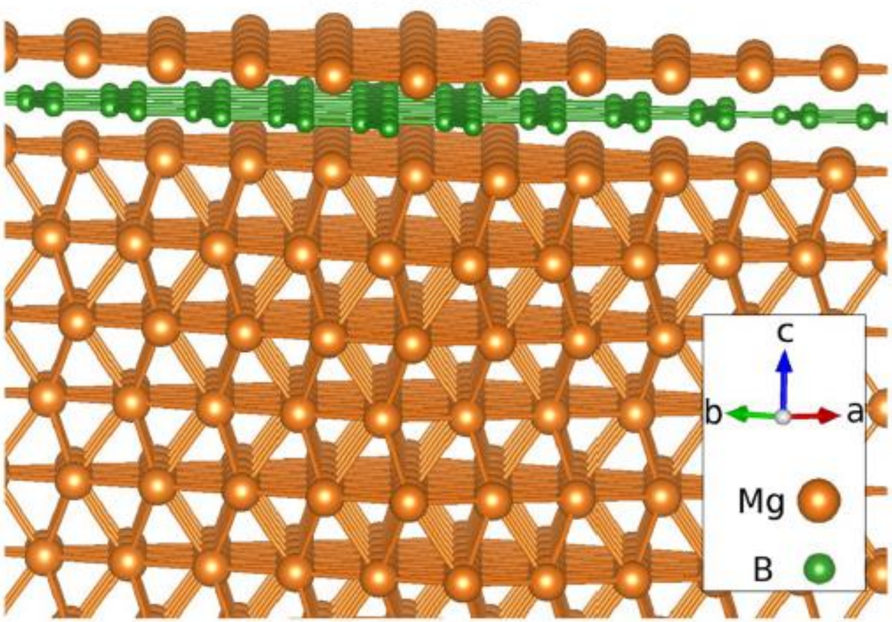
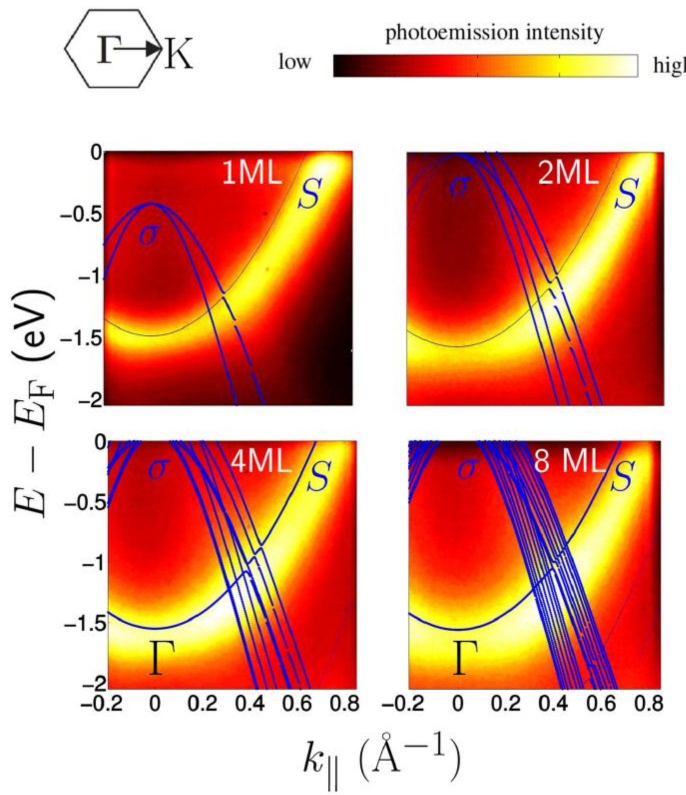
Published online: 31 October 2017

free surface





Prediction of multigap SC in M-MgB_2

PHYSICAL REVIEW B **96**, 094510 (2017)

Evolution of multigap superconductivity in the atomically thin limit: Strain-enhanced three-gap superconductivity in monolayer MgB_2

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(Received 10 May 2017; revised manuscript received 18 July 2017; published 11 September 2017)

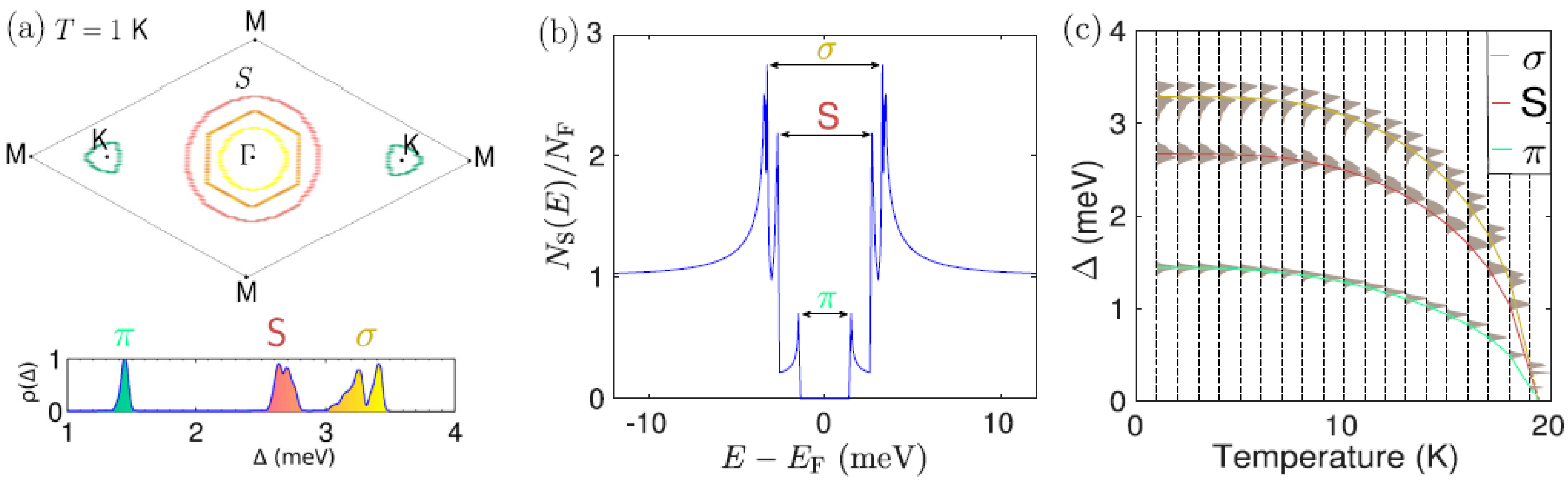

FIG. 1. The superconducting spectrum of one-ML MgB_2, calculated by anisotropic Eliashberg theory with *ab initio* input. (a) The distribution of the three superconducting gaps $\Delta(\mathbf{k}_F, T)$ on the Fermi surface: π, S (for surface), and σ, at $T = 1$ K. (b) The density of states in the superconducting state at $T = 1$ K, showing three distinct peaks corresponding to the three gaps. (c) The evolution of the gap spectrum with temperature, including the gap averages. The calculation shows that one-ML MgB_2 has $T_c \cong 20$ K.

Prediction of HTC in Hydrogenated M-MgB_2

PHYSICAL REVIEW LETTERS **123,** 077001 (2019)

Hydrogen-Induced High-Temperature Superconductivity in Two-Dimensional Materials: The Example of Hydrogenated Monolayer MgB_2

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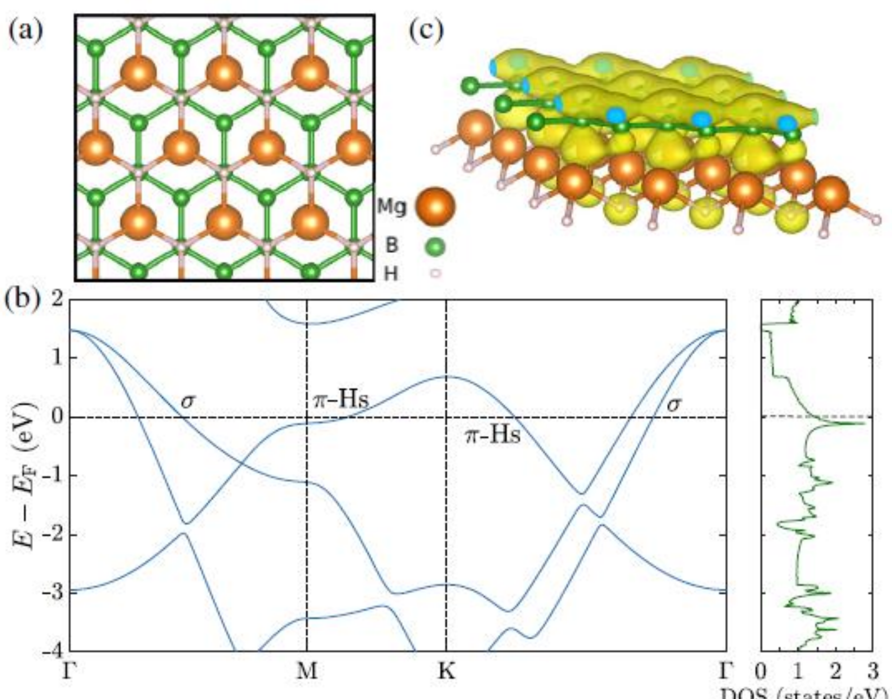

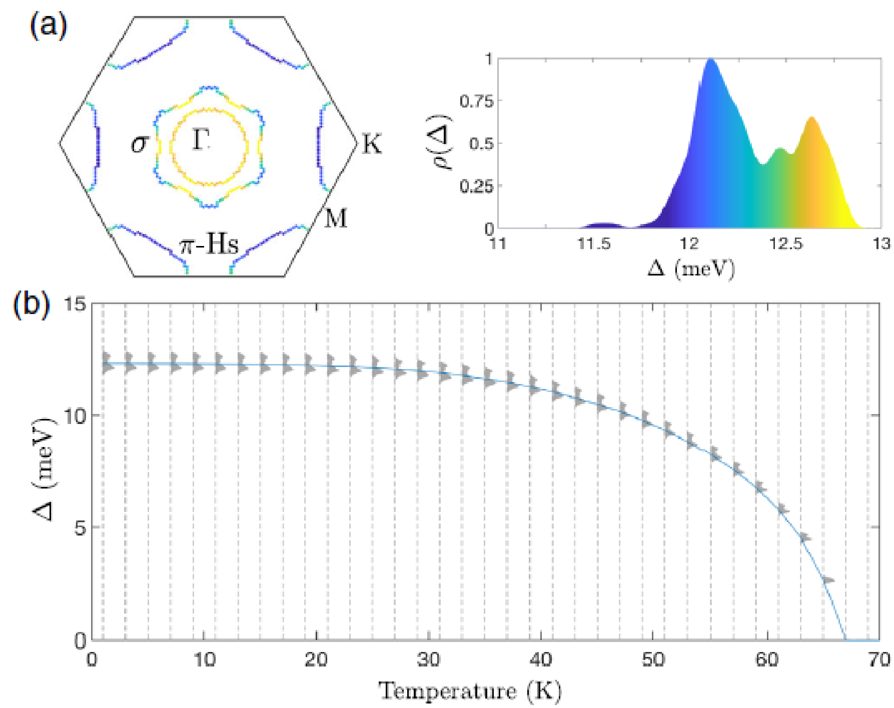

Prediction of superconductivity in M-MgB_2

High-temperature phonon-mediated superconductivity in monolayer $Mg_2B_4C_2$

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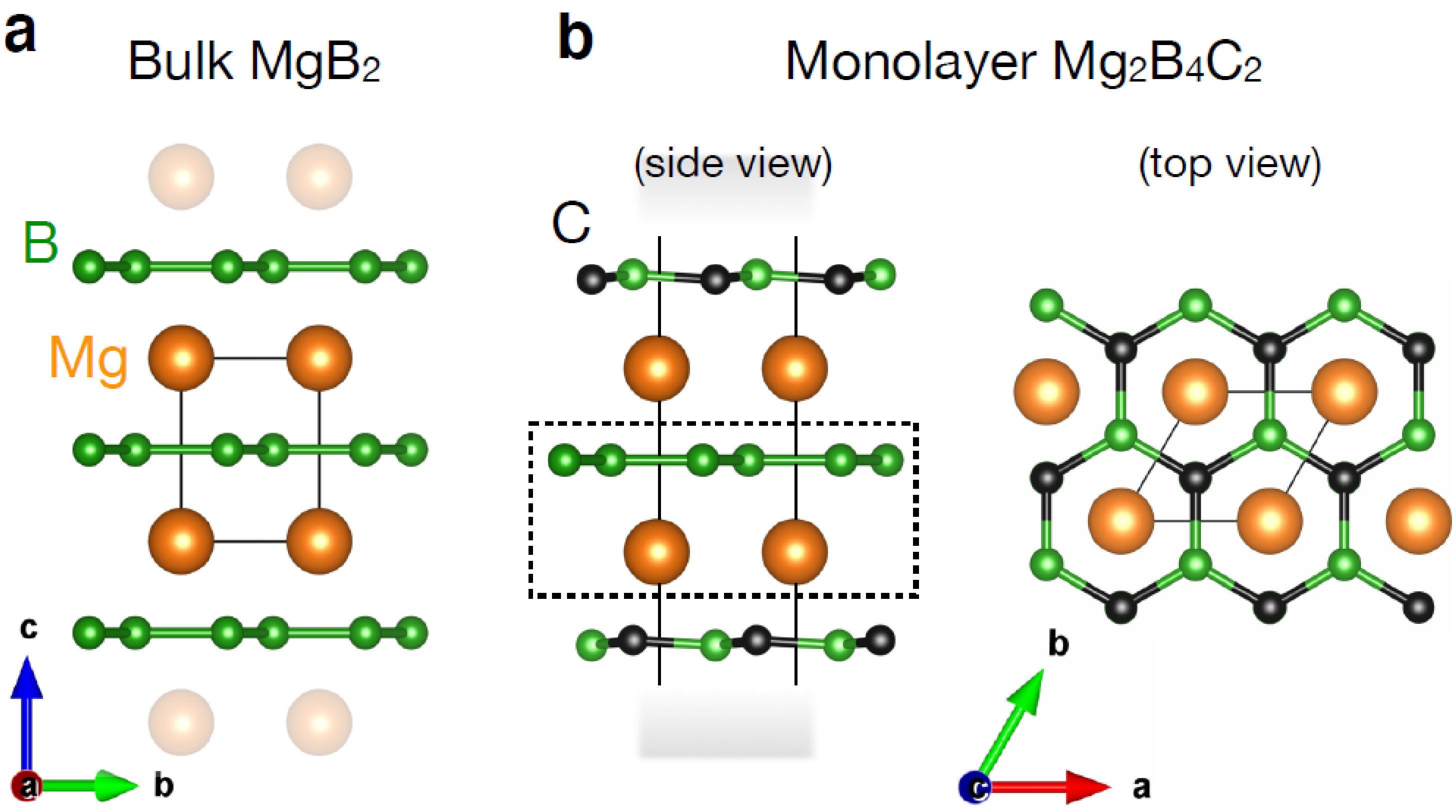

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Thank you for your attention