MgB_2: a two-gap superconductor for practical application

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Columbus Superconductors

In collaboration with

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Outline: part I

Introduction:

- Chronology of T_c until 2001
- Discovery of SC at 39K in MgB_2
- Relevant results in the firsts 5 months after the discovery

Properties of MgB_2:

- Crystal and electronic structure
- Phonon modes, e-ph coupling, isotope effect
- Exp evidence of two gaps
- Impurities and irradiation effect
- Resistivity of MgB_2 and its correlation with T_c

In the first part the discovery of MgB_2 and the relevant results in the firsts months will be briefly discussed to show how MgB_2 since the beginning has been considered a material suitable for applications.

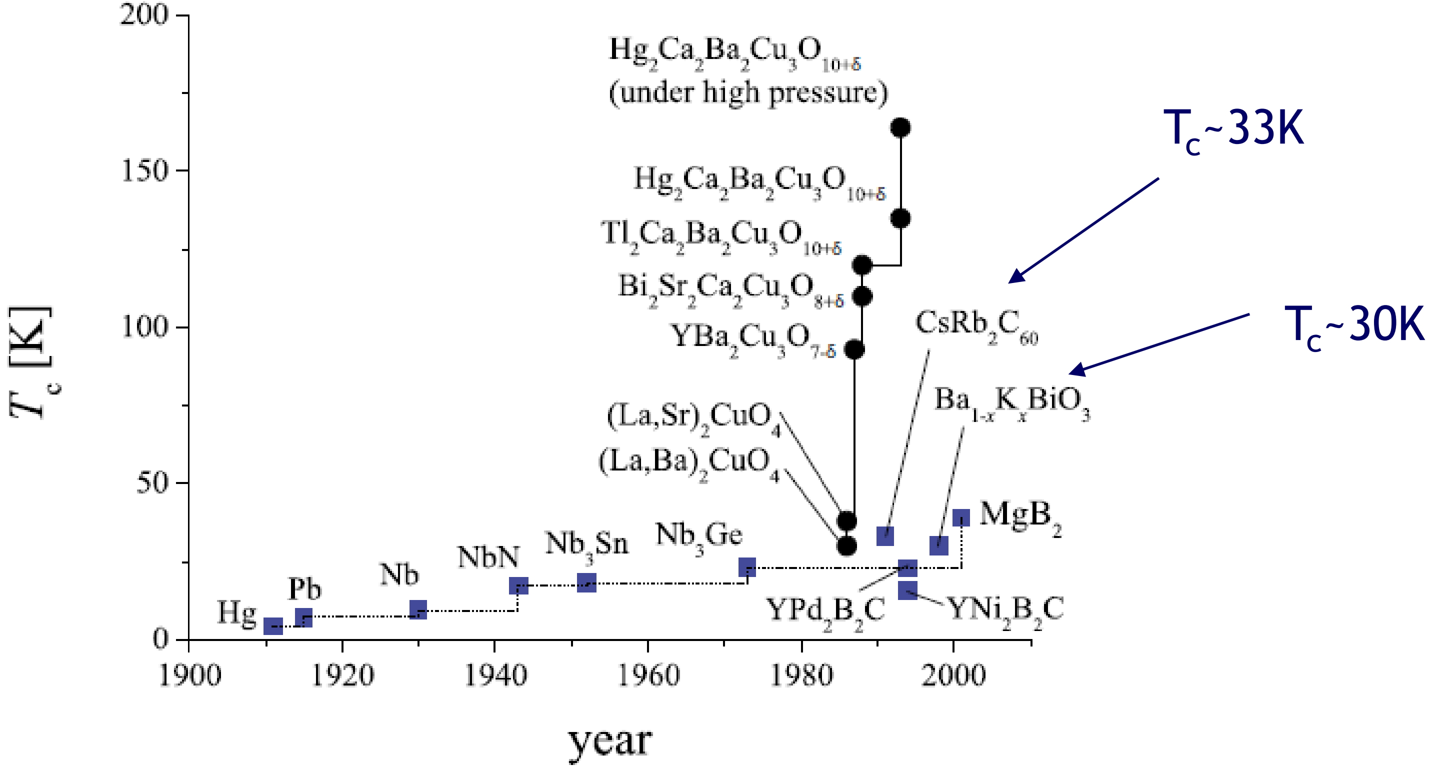
The principal aspects of the physics of MgB_2 will be also described:
discussion could not be exhaustive, the aim is to introduce the fundamental properties showing the peculiar characteristics hoping to fill you with curiosity about this compound

Outline: part II

Applications of MgB

- General properties of SC cables available on the market
- PIT fabrication options: in-situ and ex-situ
- Effect of deformation and thermal treatmenton
- Powder and conductor optimization
- Mechanical properties
- Requirements for applications
- Demonstrators of MgB_2 technology
- Market potential

Cronology of Tc until 2001



1911: zero resistivity at about 4K in Hg followed SC in other pure element
1940-1950: A15 compounds with maximum Tc at about 23K in Nb_3Sn } BCS theory framework

1986: Cu oxide SC with a maximum T_c at 138K at ambient pressure → New theoretical interpretation

How much will T_c increase in non Cu-oxyde superconductors?

Discovery

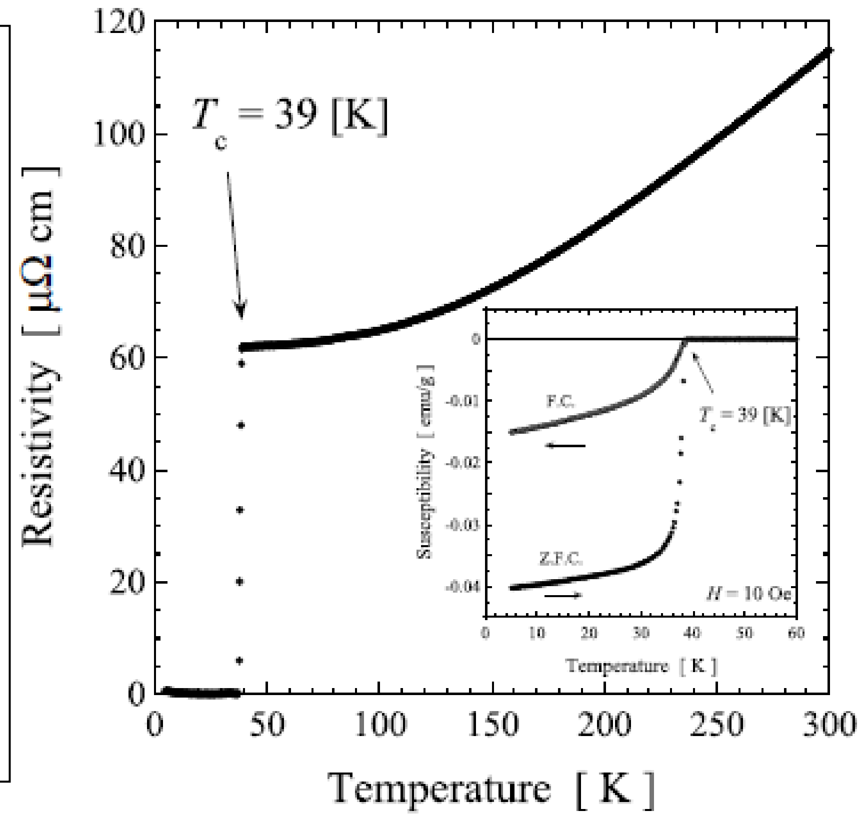
NATURE | VOL 410 | 1 MARCH 2001 | www.nature.com

Superconductivity at 39 K in magnesium diboride

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

* *Department of Physics, Aoyama-Gakuin University, Chitosedai, Setagaya-ku, Tokyo 157-8572, Japan*

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



MgB2 has opened a **new frontier into the physical properties and application of SC**. The limit of Tc in metallic superconductors had been believed to be about 30 K in the framework of the BCS theory and this discovery of unexpected high-Tc in this **simple binary intermetallic compound** has triggered enormous interests in the world.

If you run across a new metal, or an old one, **cool it down!** You might get a pleasant surprise (Paul M.Grant).

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Linked current flow

NATURE | VOL 410 | 8 MARCH 2001 | www.nature.com

Strongly linked current flow in polycrystalline forms of the superconductor MgB_2

D. C. Larbalestier*†, L. D. Cooley*, M. O. Rikel*, A. A. Polyanskii*, J. Jiang*, S. Patnaik*, X. Y. Cai*, D. M. Feldmann*, A. Gurevich*, A. A. Squitieri*, M. T. Naus*, C. B. Eom*†, E. E. Hellstrom*†, R. J. Cava‡, K. A. Regan‡, N. Rogado‡, M. A. Hayward‡, T. He‡, J. S. Slusky‡, P. Khalifah‡, K. Inumaru‡ & M. Haas‡

* *Applied Superconductivity Center, University of Wisconsin–Madison, 1500 Engineering Drive, Madison, Wisconsin 53706, USA*
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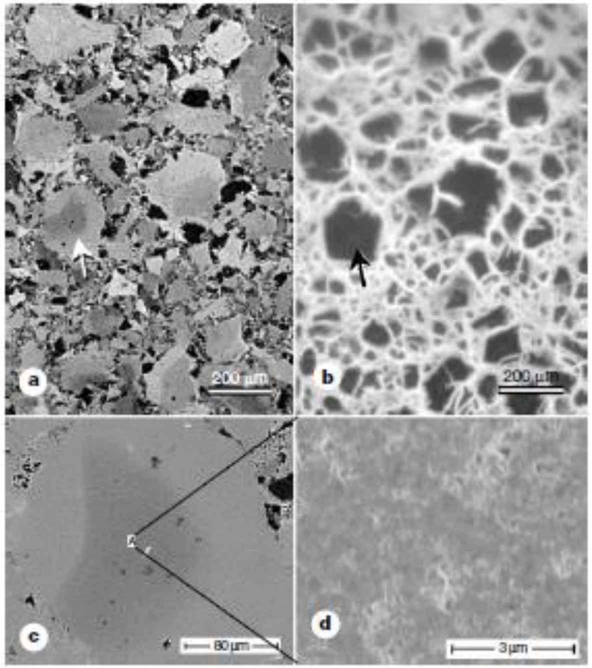
‡ *Department of Chemistry and Princeton Materials Institute, Princeton University, Princeton, New Jersey 08544, USA*



Cu-oxide SC: high T_c but large anisotropy and weak coupling across grain boundaries

→ Transport J_c in untextured samples low and sentitive to magnetic field

MgB_2: despite the multiphase, untextured, microscale subdivided nature of the firsts samples supercurrents flow in the material without exhibiting strong sensitivity to weak magnetic field

Remarkable absence of “weak link”, no need of high degree of testuring

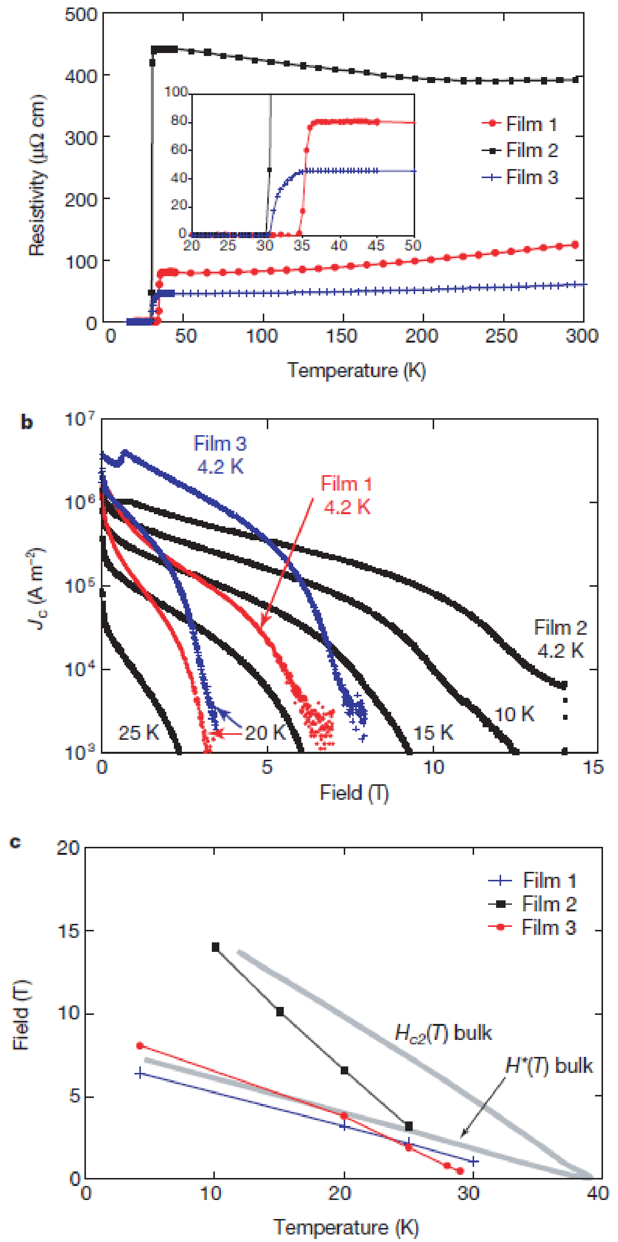
Three relevant results in the firsts 5 months (1)

NATURE | VOL 411 | 31 MAY 2001 | www.nature.com

High critical current density and enhanced irreversibility field in superconducting MgB_2 thin films

C. B. Eom*†, M. K. Lee*, J. H. Choi*†, L. J. Belenky*, X. Song†, L. D. Cooley†, M. T. Naus†, S. Patnaik†, J. Jiang†, M. Rikel†, A. Polyanskii†, A. Gurevich†, X. Y. Cai†, S. D. Bu*, S. E. Babcock*†, E. E. Hellstrom*†, D. C. Larbalestier*†, N. Rogado‡, K. A. Regan‡, M. A. Hayward‡, T. He‡, J. S. Slusky‡, K. Inumaru‡, M. K. Haas‡ & R. J. Cava‡

** Department of Materials Science and Engineering, 1509 University Avenue; and † Applied Superconductivity Center, 1500 Engineering Drive, University of Wisconsin, Madison, Wisconsin 53706, USA*
‡ Department of Chemistry and Princeton Materials Institute, Princeton University, Princeton, New Jersey 08544, USA



3 thin films:

PLD and different annealing with unintentional substitution of O on B

Enhanced J_c behaviour in magnetic field (10^6 A/cm^2 at 1T and 10^5 at 10T) and **enhanced H_{irr}** (greater than 14T at 4.2K) respect to bulk

MgB_2 has potential for in field application

Performance of MgB_2 can rival and eventually surpass that of existing SC wires

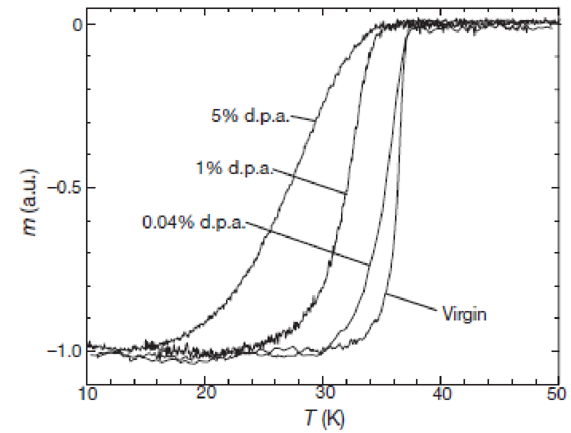
Three relevant results in the firsts 5 months (2)

NATURE | VOL 411 | 31 MAY 2001 | www.nature.com

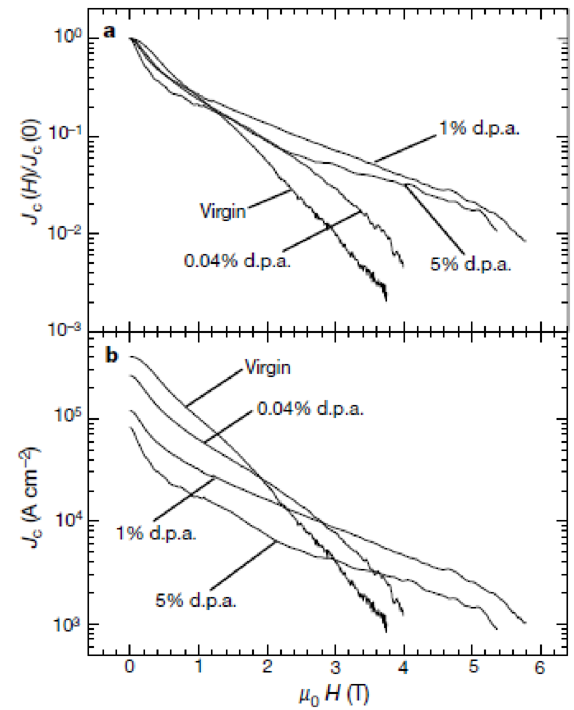
Enhancement of the high-magnetic-field critical current density of superconducting MgB_2 by proton irradiation

Y. Bugoslavsky*†, L. F. Cohen*, G. K. Perkins*, M. Polichetti*‡, T. J. Tate*, R. Gwilliam§ & A. D. Caplin*

** Centre for High Temperature Superconductivity, Blackett Laboratory, Imperial College, London SW7 2BZ, UK*
† General Physics Institute, 117942, Vavilov st38, Moscow, Russia
‡ INFM–Dipartimento di Fisica, Università di Salerno, via S. Allende, Baronissi, I-84081 (Salerno), Italy
§ EPSRC Ion Beam Centre, University of Surrey, Guildford, Surrey GU2 7RX, UK



Magnitude and field dependence of J_c are related to defect that can "pin" magnetic vortices.



A modest level of **atomic disorder** induced by proton irradiation **enhance the pinning of vortices with a significant oncrease of J_c at high field**

Chemical doping or mechanical processing can generate similar levels of disorder improving the performance

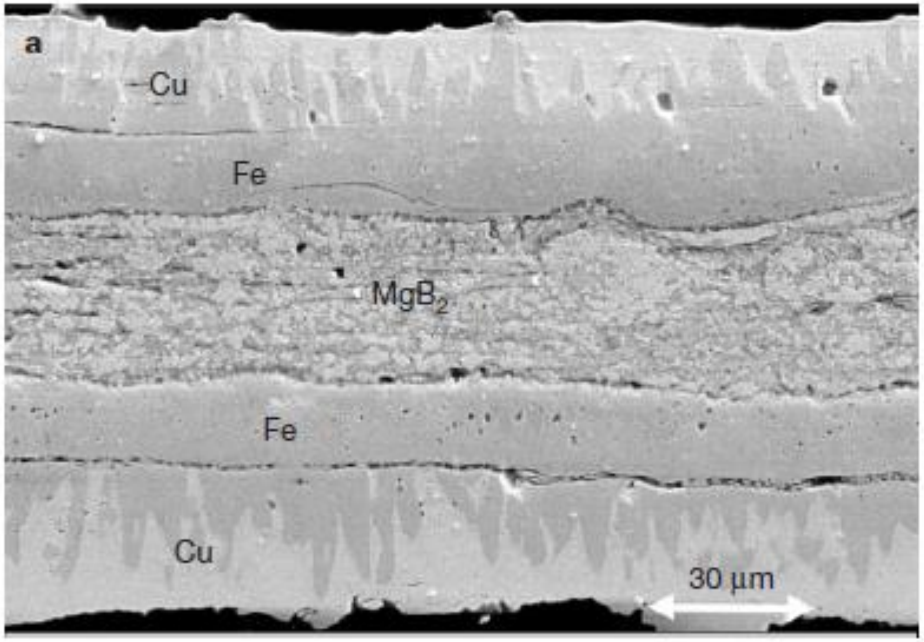
Three relevant results in the firsts 5 months (3)

NATURE | VOL 411 | 31 MAY 2001 | www.nature.com

High critical currents in iron-clad superconducting MgB_2 wires

S. Jin, H. Mavoori, C. Bower & R. B. van Dover

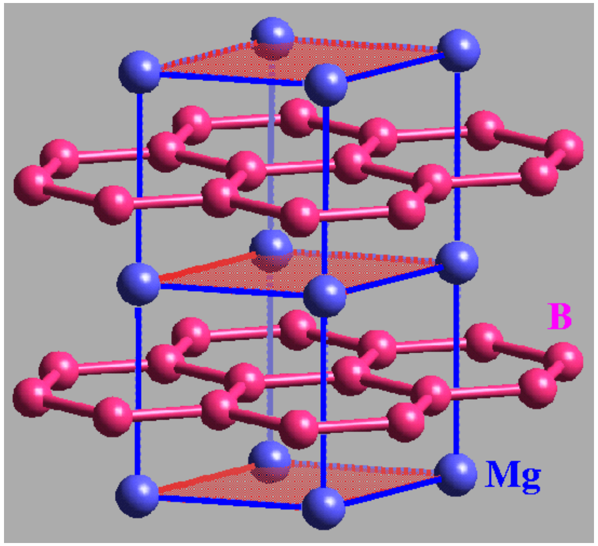
Agere Systems/Lucent Technologies, Murray Hill, New Jersey 07974, USA



Technically useful bulk superconductors must have high Jc, at operating temperatures.
They also require a **normal metal cladding** to provide
parallel electrical conduction, thermal stabilization, and mechanical protection
of the generally brittle superconductor cores.

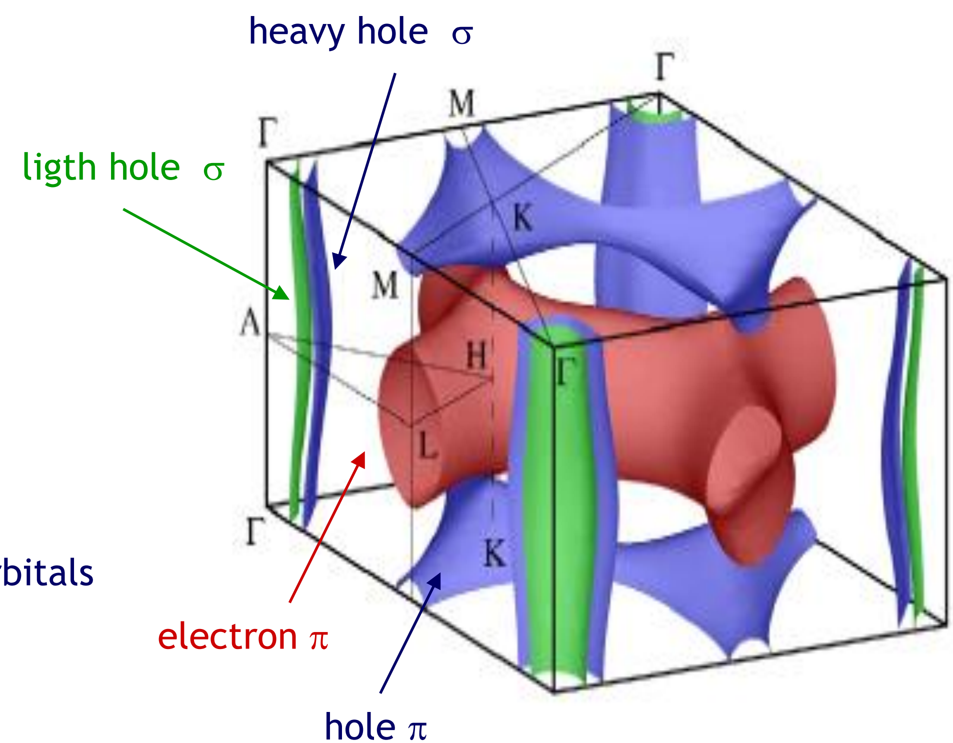
The paper demonstrated a transport Jc in excess of 85,000 A/cm^2 at 4.2 K
(a value high enough for power transmission cable)

Crystal and electronic structure



MgB_2 has the AlB_2 structure
with a=3.08Å and c=3.51Å (space group P6/mmmm)

- stacks of 2D honeycomb B layer
- Mg atoms between the B layer at the centre of the hexagons



Band structure is derived by B electrons.

There are 4 conduction bands formed by

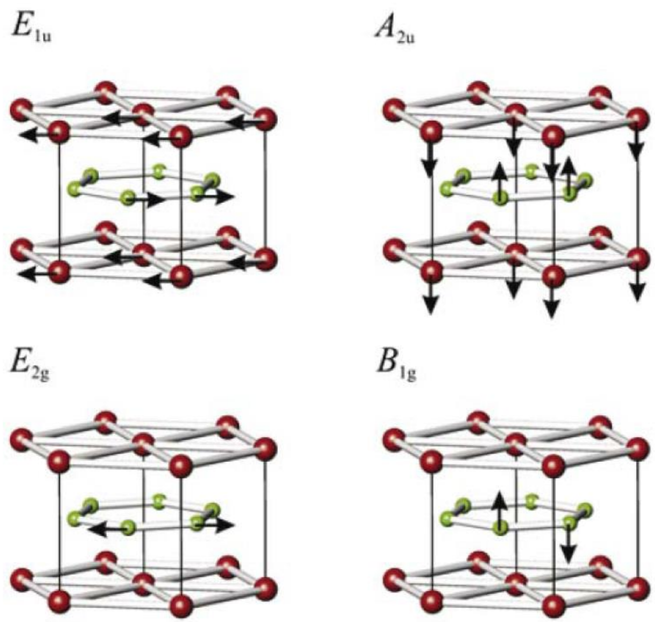
- two **σ bands** derived from the σ –bonding $p_{x,y}$ orbitals
- two **π bands** derived by π-bonding (hole like) and anti-bonding (electron like) p_z orbitals

σ states are **2D**, confined in the B planes
π states are **3D** extending in all directions

→ **Small Impurity interband scattering**

In plane and out of plane orbitals, different parity

Phonon modes



The investigation of phonons is important because they play a crucial role in superconductivity

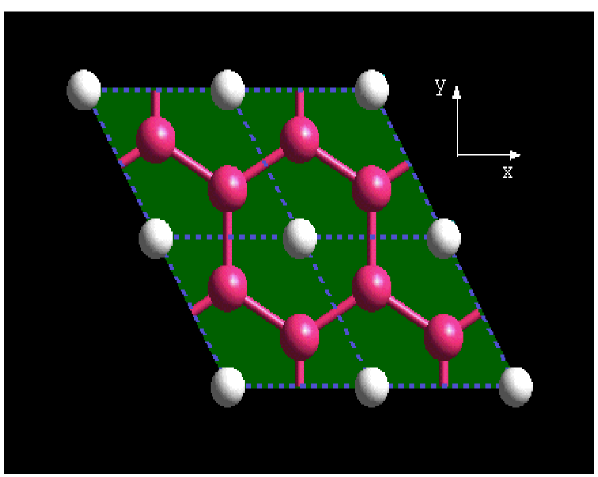
E_{1u}: in plane B and Mg displacements

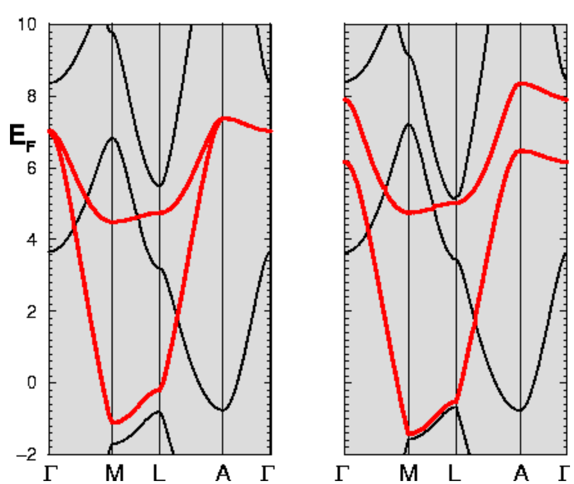
A_{2u}: out of plane B and Mg displacements

E_{2g}: B in plane bond stretching

B_{1g}: B out of plane bond bending

Theoretical investigation show planar boron σ **bands** coupled with **E_{2g} phonon modes**





B motions change the boron orbital overlap with shift and splitting near the Fermi level

↓

Strong EP coupling

Isotope effect

In order to understand the role of phonons in SC the isotope effect is a crucial information

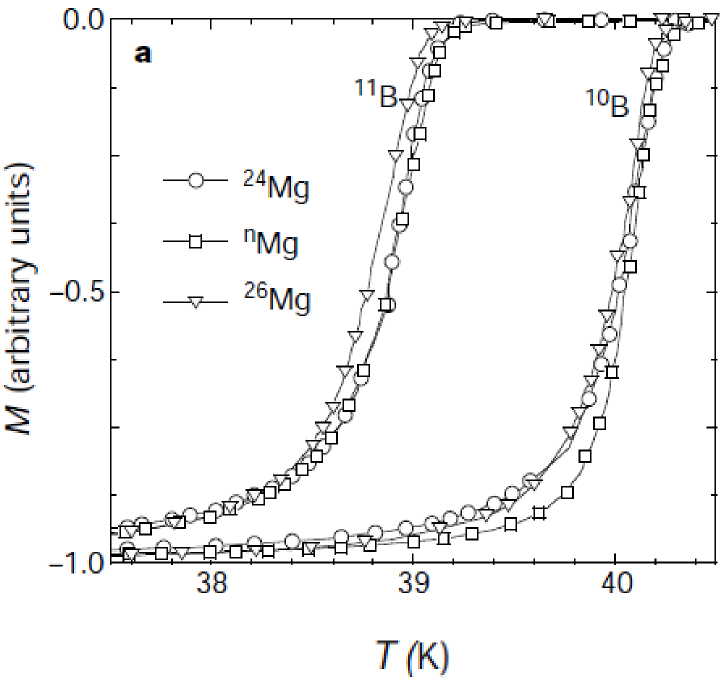
BCS isotope coefficient

$$\alpha = -\frac{\Delta \ln(T_c)}{\Delta \ln M}$$

T_c → Critical temperature

M → Isotopic mass of the element

Multi-element materials $\alpha_{tot} = \sum_i \alpha_i$ MgB_2 $\alpha_{MgB_2} = \alpha_B + \alpha_{Mg}$



NATURE | VOL 411 | 24 MAY 2001 | www.nature.com

The measurement of the isotope effect as the first evidence of the phonon mediated character of the coupling mechanism

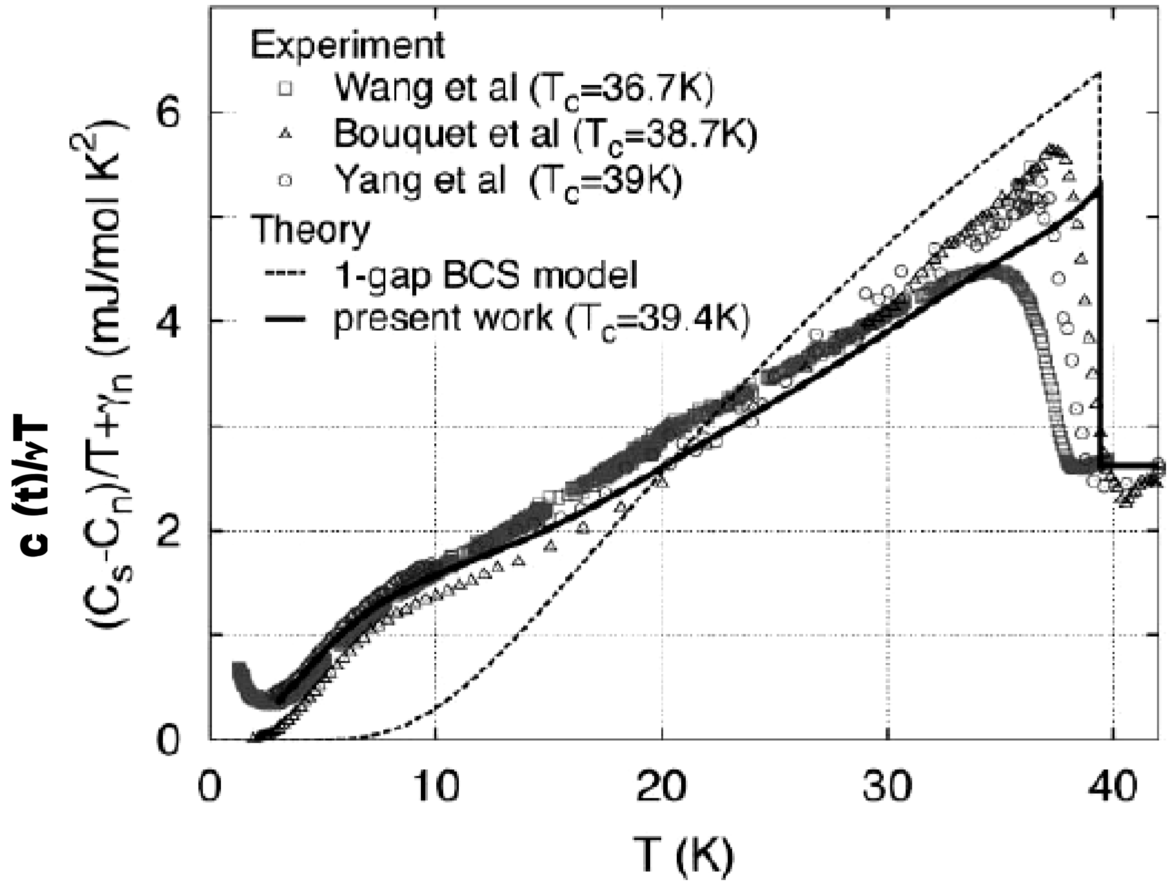
- $T_c(^{24}MgB_2) - T_c(^{26}MgB_2) \approx 0.07$ K ⟶ $a_{Mg} \approx 0.02$
- $T_c(Mg^{10}B_2) - T_c(Mg^{11}B_2) \approx 1$ K ⟶ $a_B \approx 0.3$

$\alpha_{tot} = \alpha_B + \alpha_{Mg} \approx 0.32$ $\alpha_{BCS} = 0.5$

$\alpha(MgB_2) < a_{BCS}$?

The anomalous value of the isotope coefficient is **still an open question**

Experimental evidence of two gap

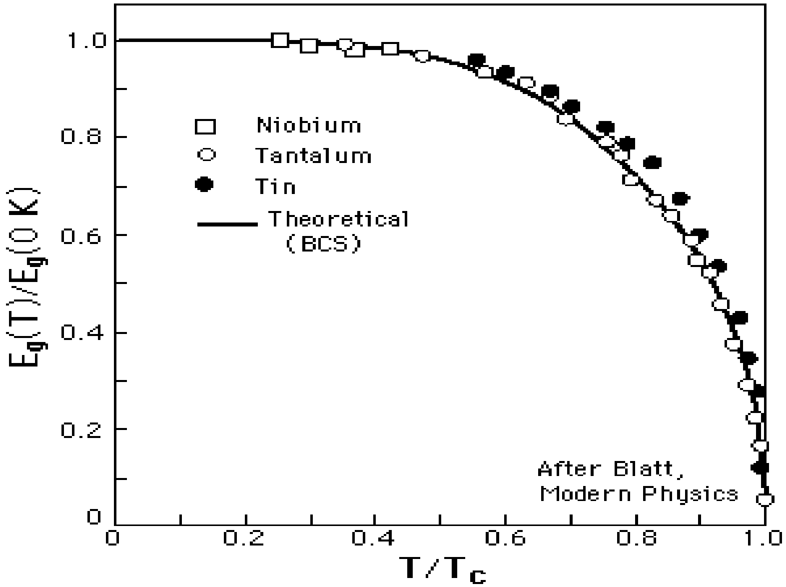


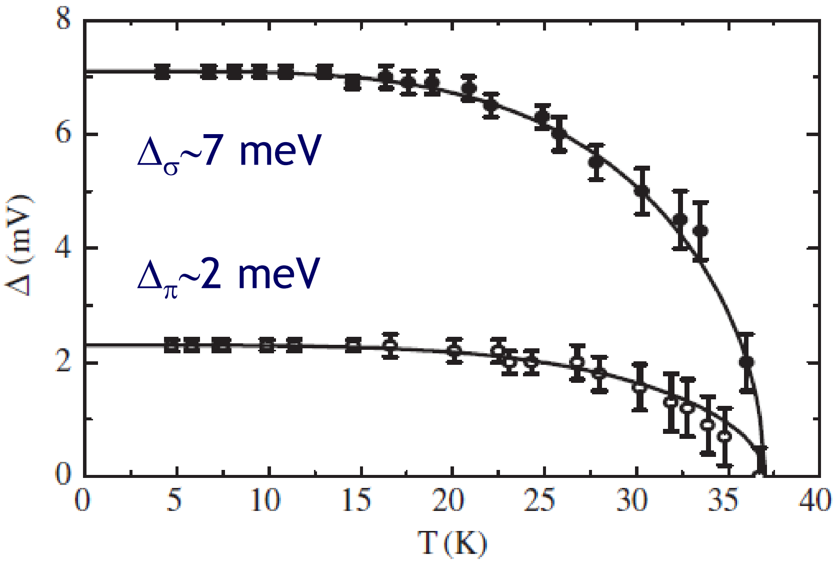
T_c = 38.5 K
$\Delta_\sigma(0)$ = 6.3 meV
$\Delta_\pi(0)$ = 1.8 meV

Electronic specific heat data cannot be explained by the one gap BCS model with T_c of 39.4K.
At lower T data vales are higher than BCS showing a decrease to zero suggestive of another transition, a strong indication of a second, smaller gap.
The two gaps model is in excellent agreement with the experiments,

Two gap superconducting state

MgB_2 is a **conventional BCS** superconductor: **Cooper pairs form via e-ph interaction.**
But MgB_2 is **not an ordinary** superconductor with a **one temperature dependent energy gap Δ(T)**





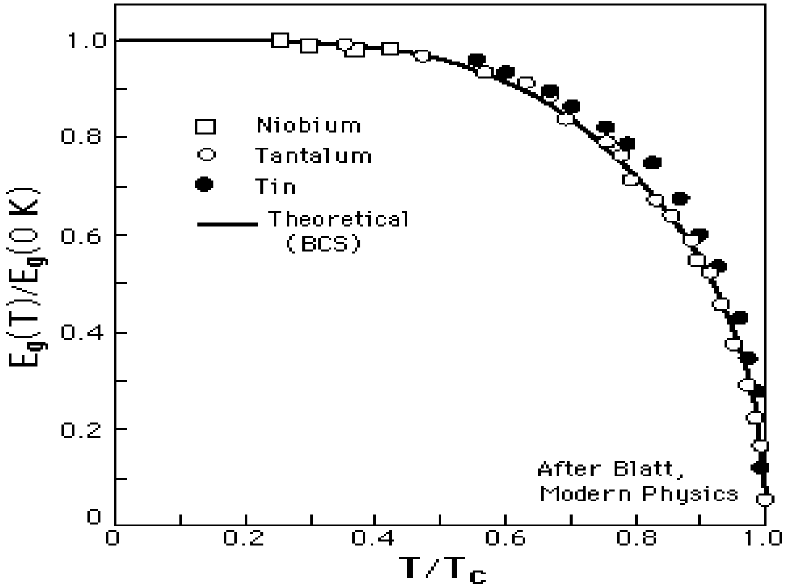
Two gaps exist in MgB2 (data in figure are from Scanning tunneling spettroscopy) and **disappear at T_c.**

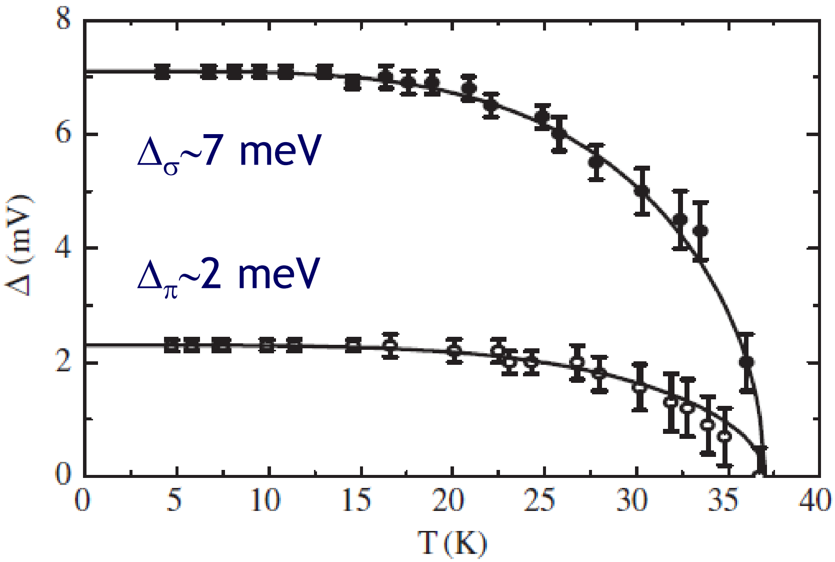
Two gaps arise from the existence of the two bands, but the **small interband scattering** distinguishes MgB_2 from other SC's with multiple bands at FS where the interband scattering smears out the distinct characteristic of the bands

Small Impurity interband scattering → **Cooper pairs are not mixed maintaining their characteristics with two perfectly separated gaps**

Two gap superconducting state

MgB_2 is a **conventional BCS** superconductor: **Cooper pairs form via e-ph interaction.**
But MgB_2 is **not an ordinary** superconductor with a **one temperature dependent energy gap Δ(T)**





BCS equation for T_c

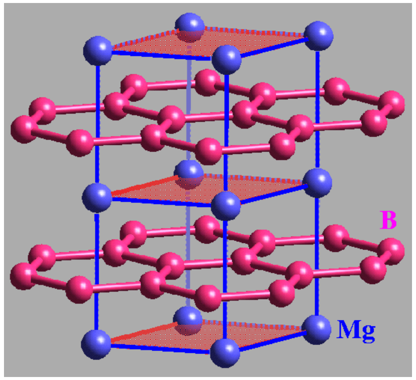
$$T_c = \frac{\omega_D}{1.2}\exp\left(-\frac{1}{\lambda_{eff}}\right)$$

$\lambda_{\sigma\sigma}=0.96$	$\lambda_{\sigma\pi}=0.17$
$\lambda_{\pi\sigma}=0.23$	$\lambda_{\pi\pi}=0.29$

	Single-gap	multi-gap
λ	λ ~0.6	λ_{max} ~1
ω_{ph}	75 meV	75 meV
T_c	19 K	39 K

Small Impurity interband scattering → **Cooper pairs are not mixed maintaining their characteristics with two perfectly separated gaps**

Effect of impurities: Al and C doping



σ states are **2D**, confined in the B planes, **strongly coupled with E_{2g}**
π states are **3D** extending in all directions, **weakly coupled with phonons**

Different types of impurities can affect selectively σ and π mean free paths with distinct consequences on the transport properties: the most deeply investigated are **Al on Mg** and **C on B.**

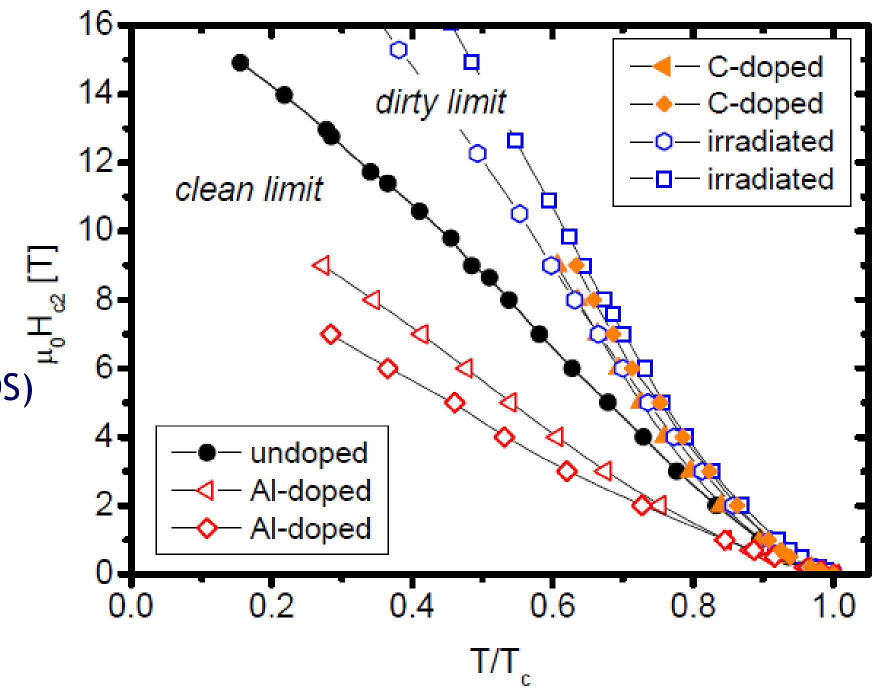
Both substitutions **reduce T_c**: **e-doping** reduces the DOS (σ band filling)

Al on Mg affects only the π **mean free path**:
π bands are in "dirty limit"
σ bands are in "clean limit"

C on B affects the π **and** σ **mean free path**:
π and σ bands are in "dirty limit"

Al doped samples are in clean limit and **H_{c2} decreases** (weakening of the coupling due to the decrease of the DOS)

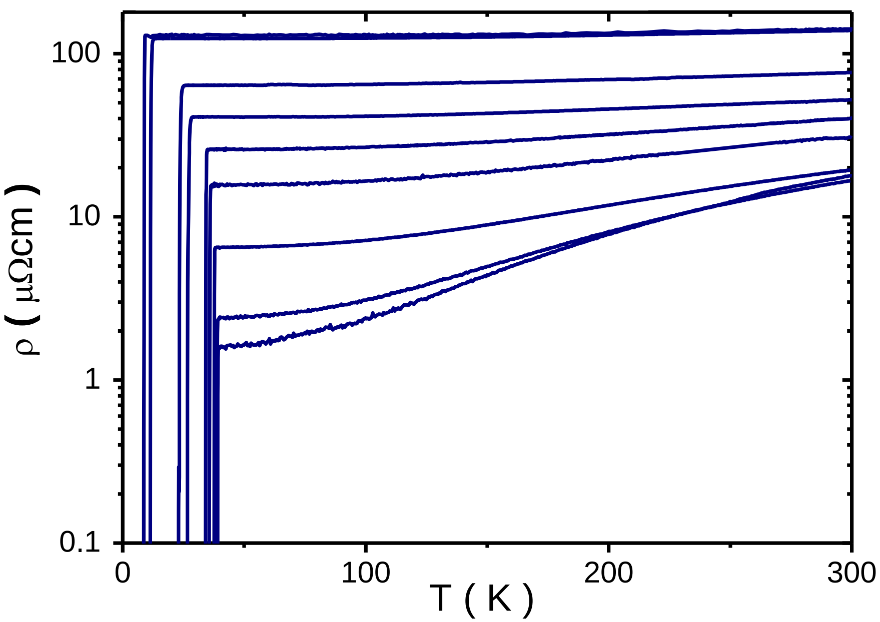
C doped samples,
as well as **irradiated samples,** are in dirty limit
and **H_{c2} increases**
(decrease of the DOS but with a decrease of the mfp)



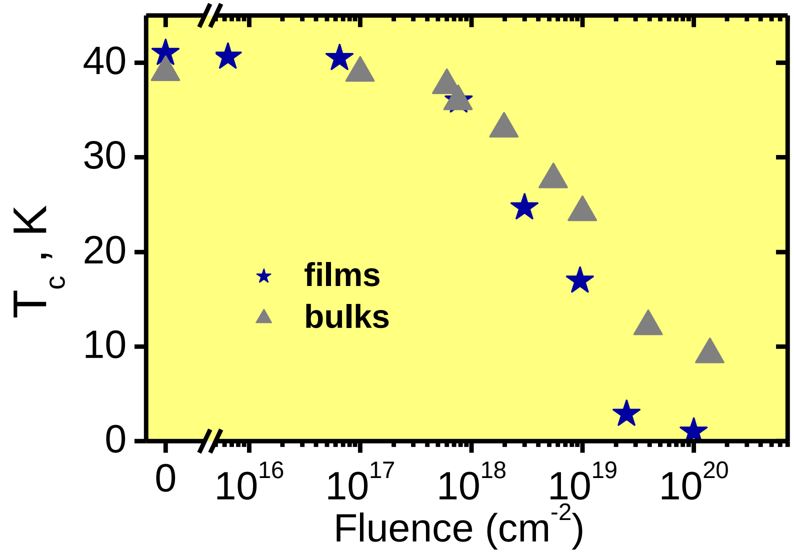
Effect of irradiation

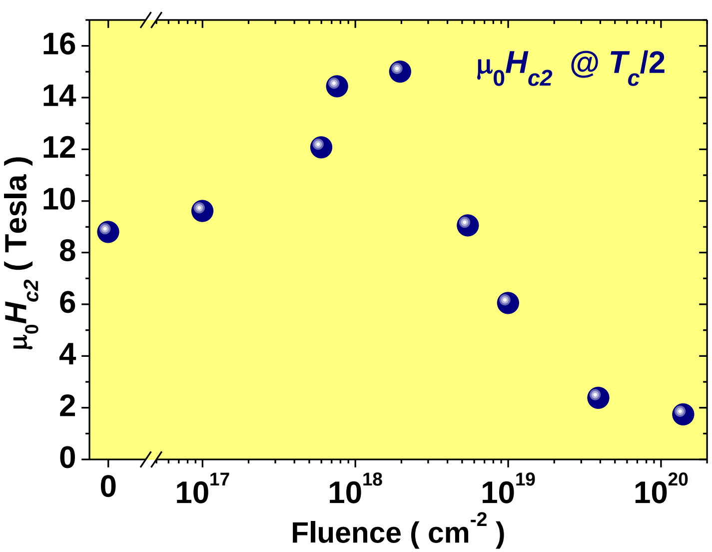
Neutron irradiation: a way to introduce defect without doping demonstrating the role of interband scattering in **suppress T_c** and **producing the merging of the two energy gaps**

Tarantini et al.
PHYSICAL REVIEW B 73, 134518 (2006)



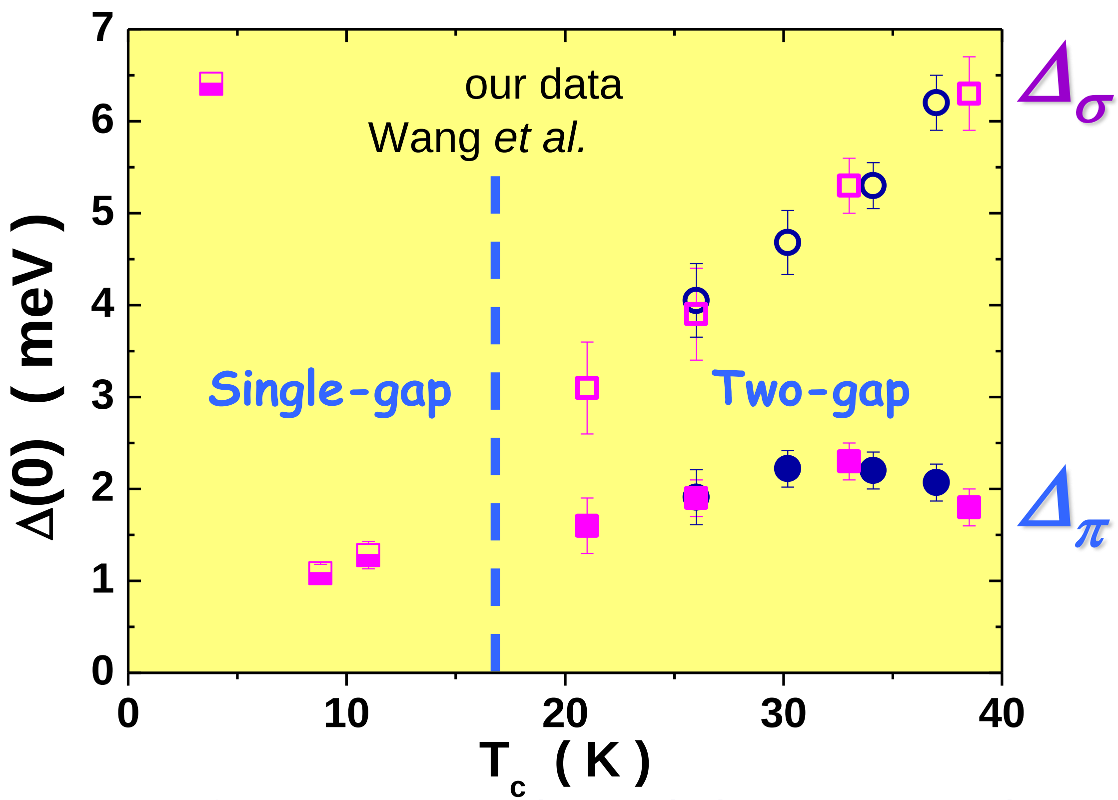
T_c decreases down to 6K, resistivity increases

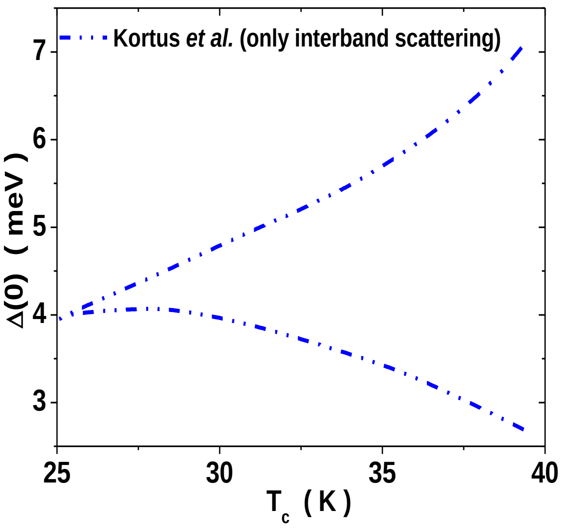




Hc2 strongly increases up to fluence of 2×1018 cm^{-2}, while T_c is only slightly decreased.
At higher fluence, both Tc and Hc2 are strongly suppressed

From two- to single gap superconductor





The cross-over from two- to single-gap behaviour occurs between 21 and 11 K

Δ_σ decreases linearly with irradiation

Decreasing T_c, Δ_π increases down to ~30 K, then smoothly decreases

⇨ ***Interband scattering***

M.Putti, C.Tarantini *et al. Physical Review Letters* 96, 077003 (2006)

D. Daghero, C. Tarantini *et al., Physical Review B* 74, 174519 (2006)

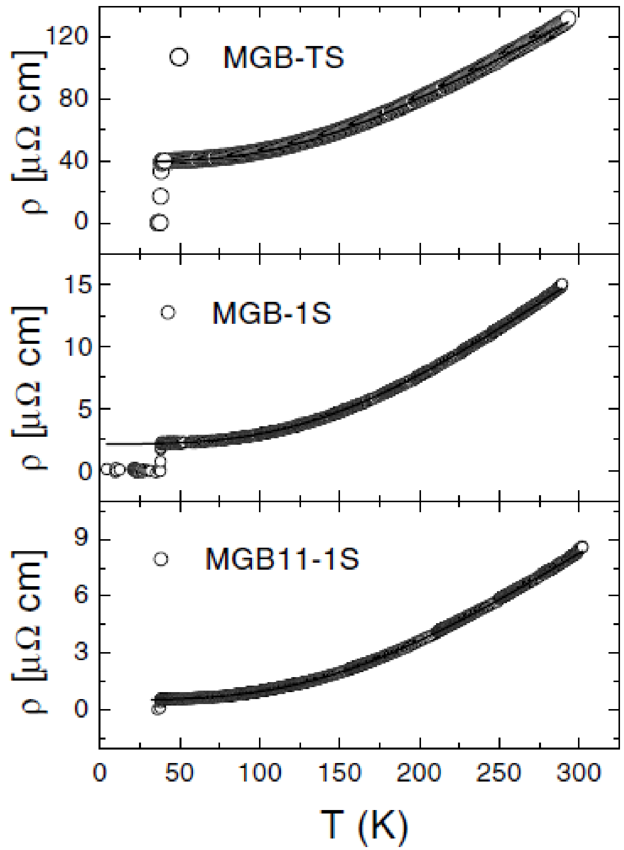
Resistivity of MgB_2: ρ_0 and T_c correlation

INSTITUTE OF PHYSICS PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY
Supercond. Sci. Technol. **16** (2003) R17–R27 PII: S0953-2048(03)55895-X

TOPICAL REVIEW

The widely variable resistivity of MgB_2 samples

John M Rowell[1]



- **T_c~39K** in samples with very low resistivity (10 μΩ cm at 300K and 0.5 μΩ cm at 40K)
- **Tc~39K** in samples with high resistivity
- The behavior of rho Vs T is always T^2 to T^3

No correlation between rho and T_c?

Mazin:
Evidence of band disparity,
No interband scattering, No suppression of T_c

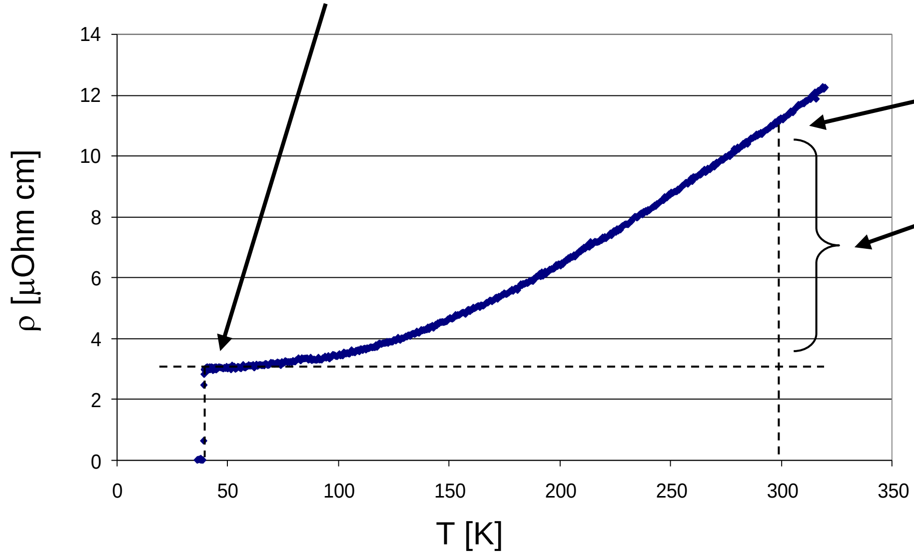
Rowell:
the resistivity increase in most cases could be simply ascribed to a **weak connection between the grains** which causes a reduction in the **effective current-carrying cross-sectional area** of the sample.

Effective area fraction

$\rho_0 = \rho$ (40 K)

ρ (300 K)

$\Delta\rho = \rho$ (300 K) – ρ (40 K)



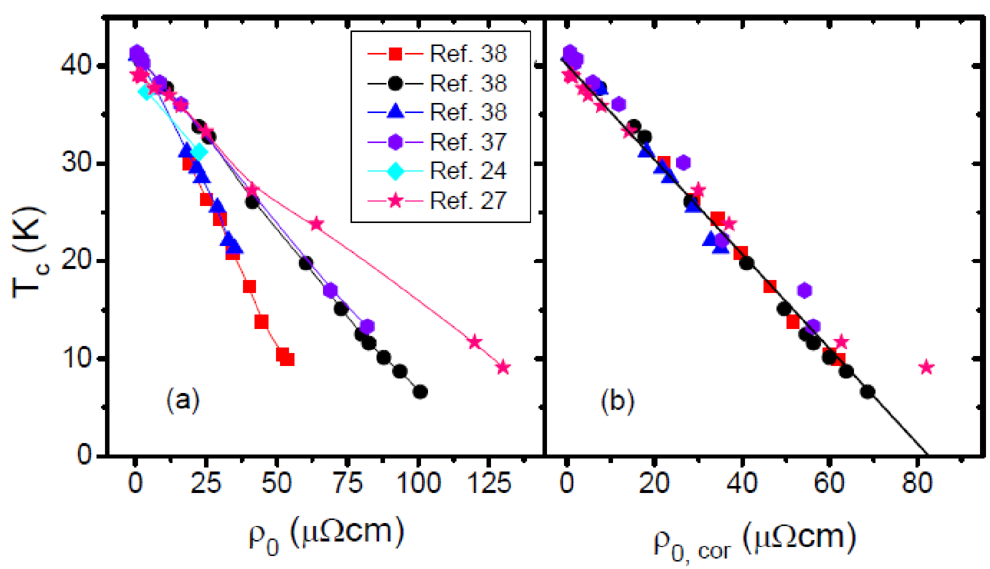
Assuming $\Delta\rho$ = cost, $\Delta\rho_g$ **= 7.5 μOhm cm**

like in the case of perfect connectivity

$$\rho_{0,g} = \frac{\Delta\rho_g}{\Delta\rho}\rho_0$$

Effective area fraction

$$A_f = \frac{\Delta\rho_g}{\Delta\rho}$$



Tc versus residual resistivity of several series of irradiated films or bulk:

All data collapse on the same line using the "Rowell" normalized resistivity

M Putti, R Vaglio, J M Rowell

Supercond. Sci. Technol. **21** (2008) 043001 (25pp)