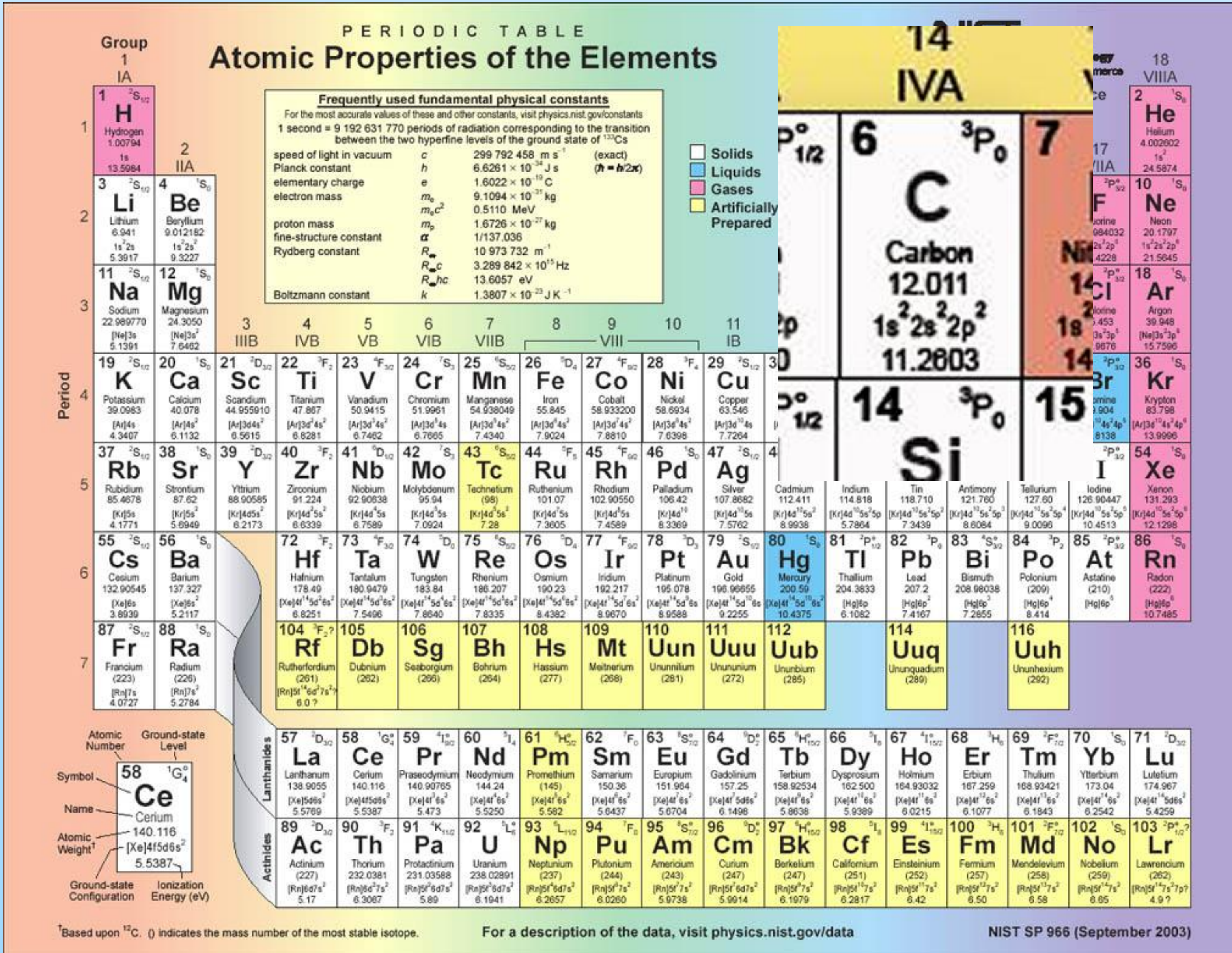
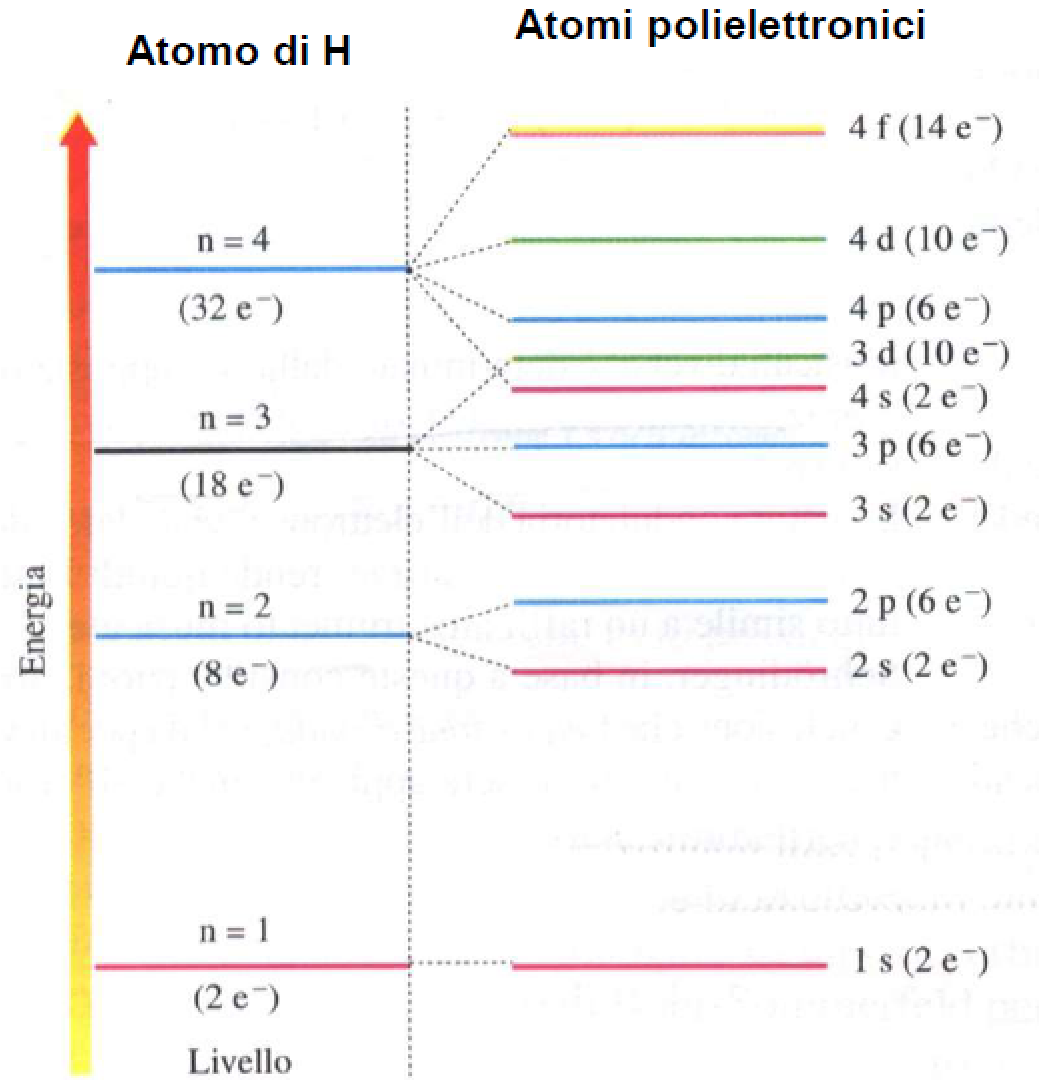
Carbon, its allotropic states and Graphite

M. Riccò


PERIODIC TABLE
Atomic Properties of the Elements
Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of 133Cs
speed of light in vacuum c 299 792 458 m s-1 (exact)
Planck constant h 6.6261 × 10-34 J s
elementary charge e 1.6022 × 10-19 C
electron mass me 9.1094 × 10-31 kg
mec2 0.5110 MeV
proton mass mp 1.6726 × 10-27 kg
fine-structure constant α 1/137.036
Rydberg constant R∞ 10 973 732 m-1
R∞c 3.289 842 × 1015 Hz
R∞hc 13.6057 eV
Boltzmann constant k 1.3807 × 10-23 J K-1
Solids
Liquids
Gases
Artificially Prepared
Group
Period
Lanthanides
Actinides
Atomic Number
Ground-state Level
Symbol
Name
Atomic Weight
Ground-state Configuration
Ionization Energy (eV)
14
IVA
6
C
Carbon
12.011
11.2603
14
Si
Based upon 12C. () indicates the mass number of the most stable isotope.
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2003)

- ^{12}C Isotope→ natural abundance (98.93%, S=0)
- ^{13}C Isotope → important for NMR (1.07%, S=1/2)
- ^{14}C Isotope → important for archaeological dating (average lifespan 5730 years)



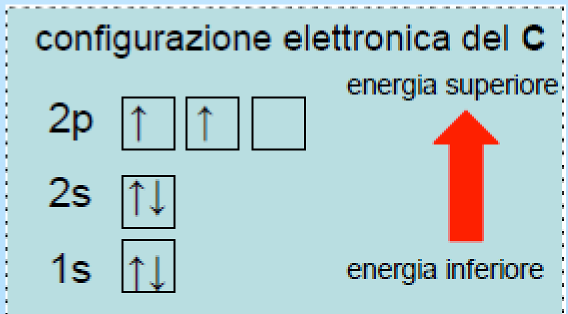
The energy of each electron in multi-electron atoms depends not only on *n*, but also on *l*; a fundamental consequence of **inter-electronic interactions**.

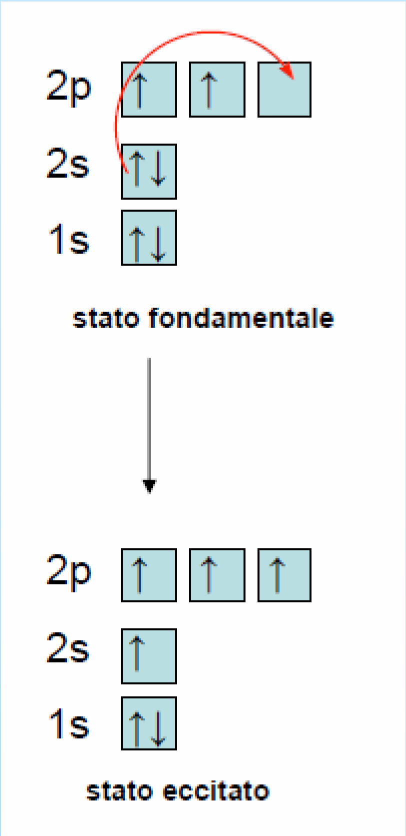
Splitting of energy levels into multiple sublevels with distinct and increasing energy, for a given *n* value, **as *l* increases**.

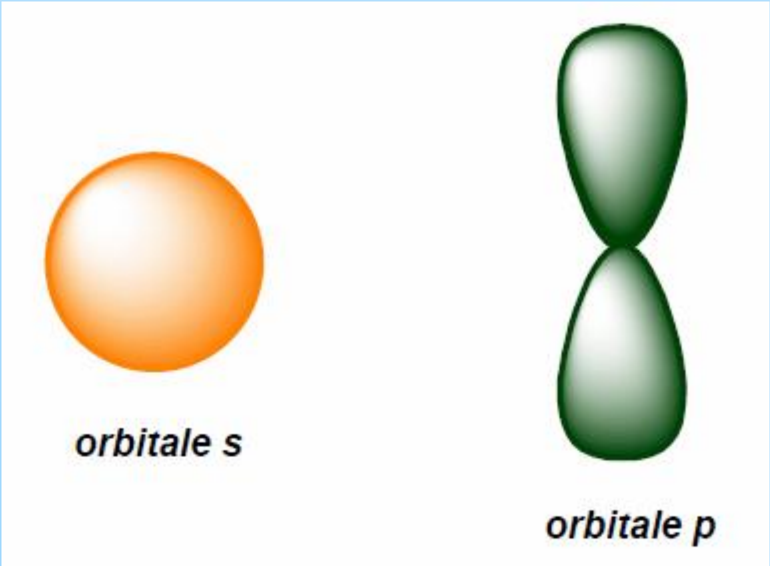
Between level 3 and level 4, there is an **overlap of energy levels**.

sp^3 hybridization

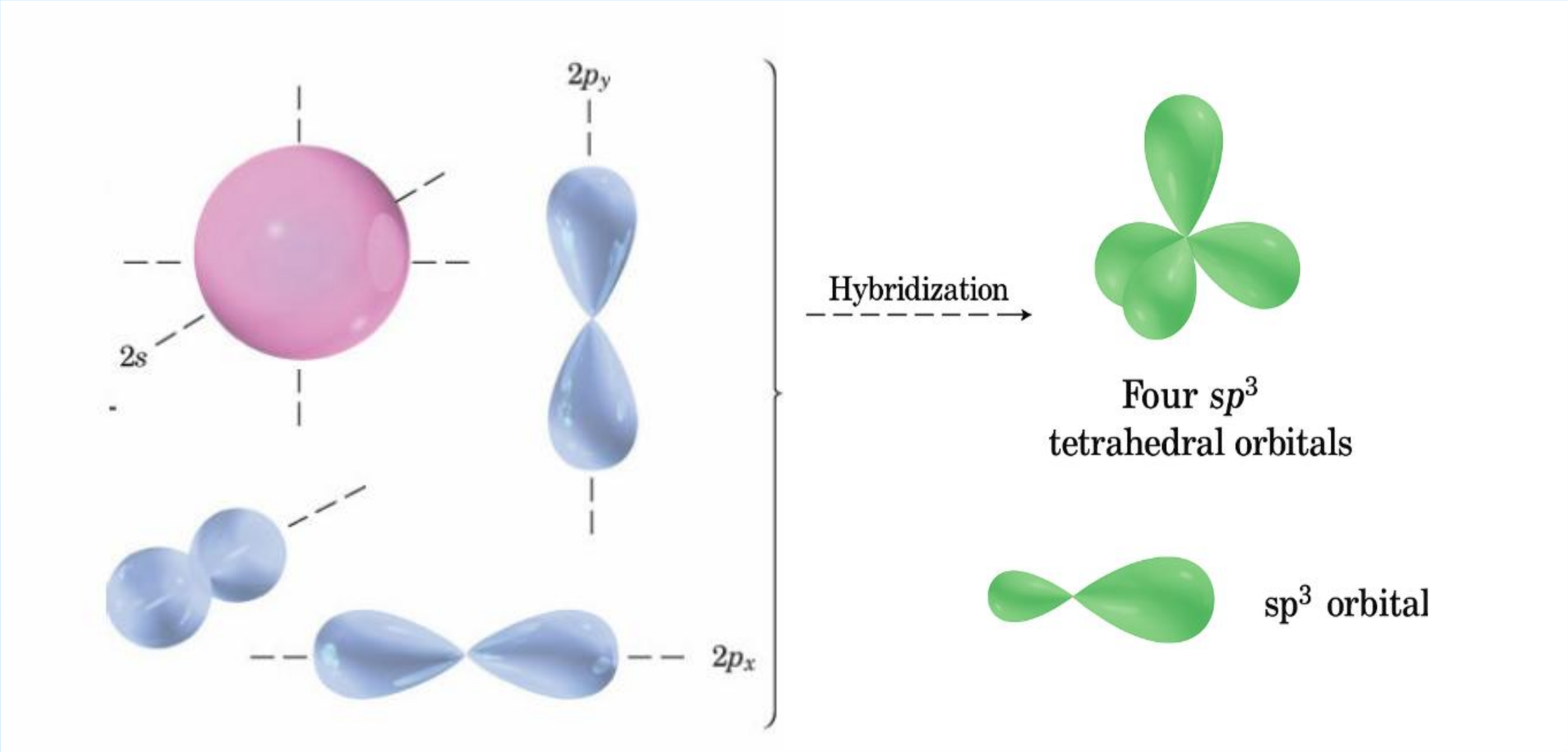
Configuration: [He] $2s^2\ 2p^2$





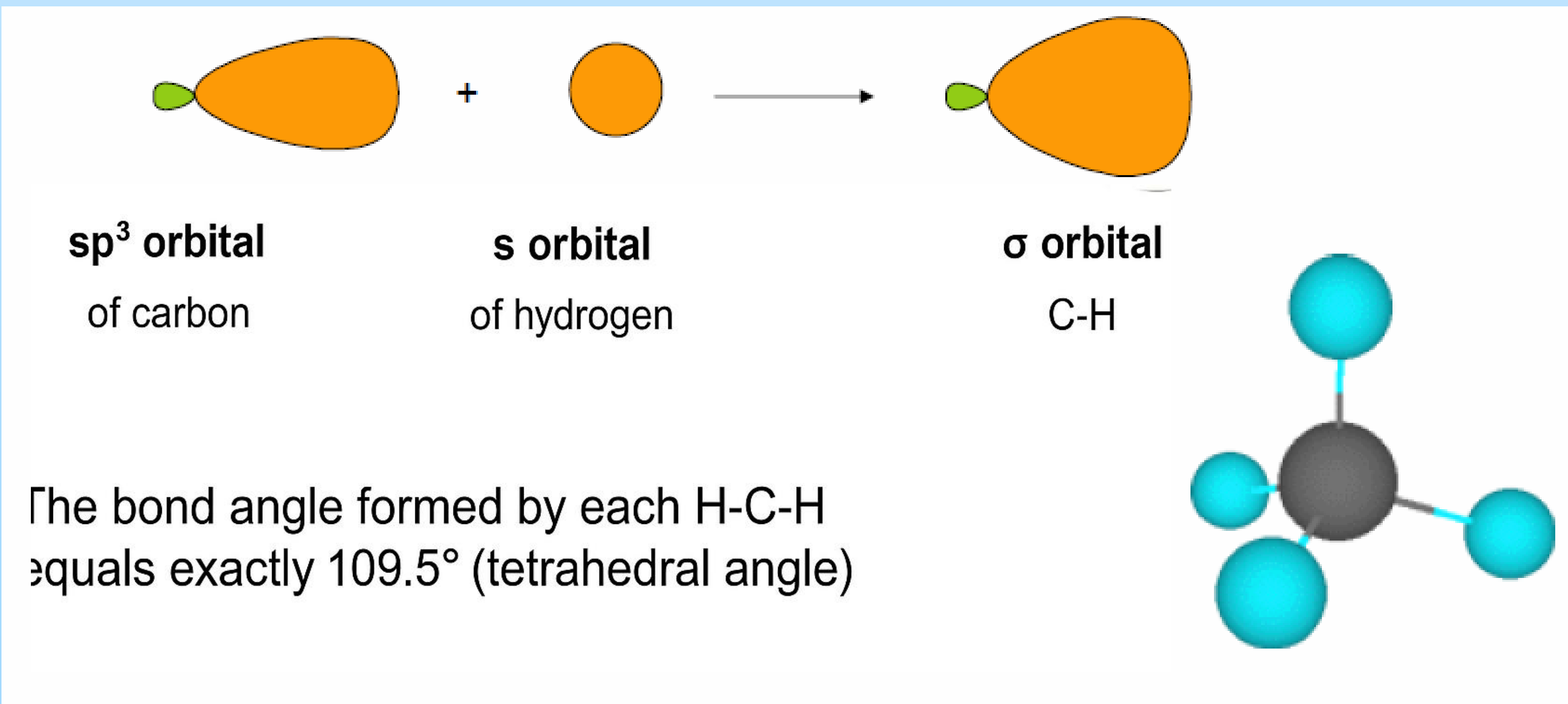


sp^3 hybridization

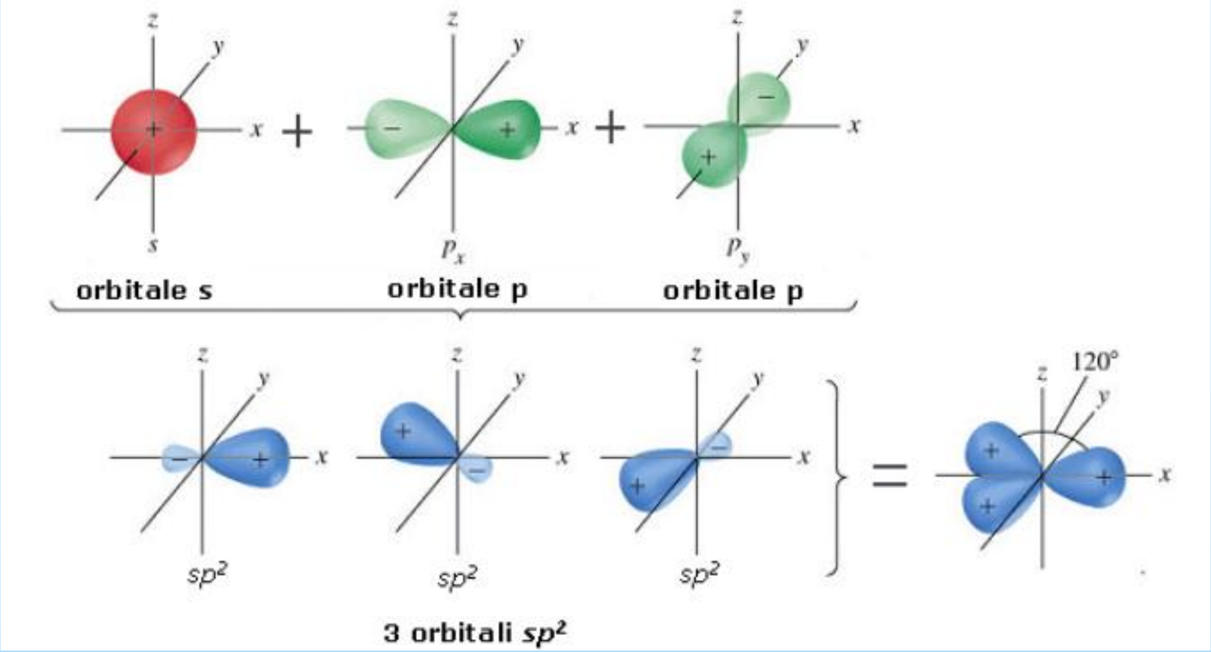


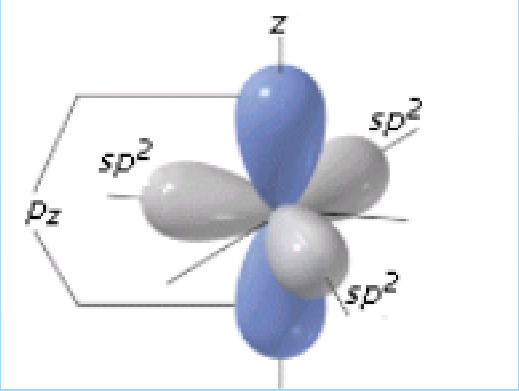
sp^3 hybridization

Methane

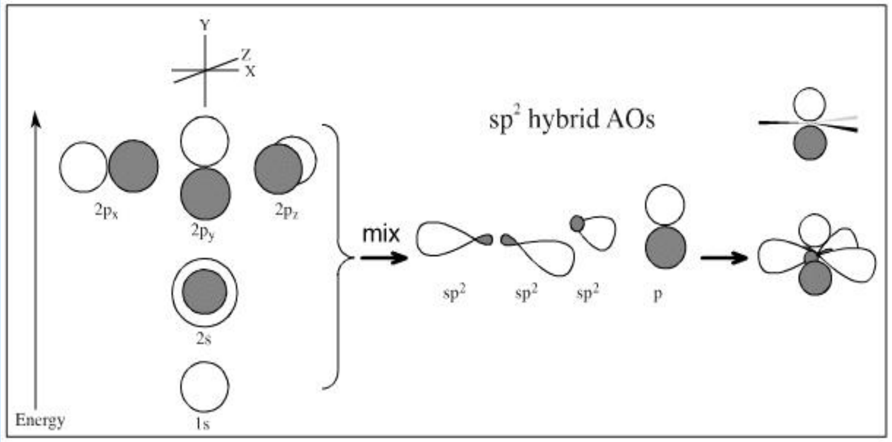


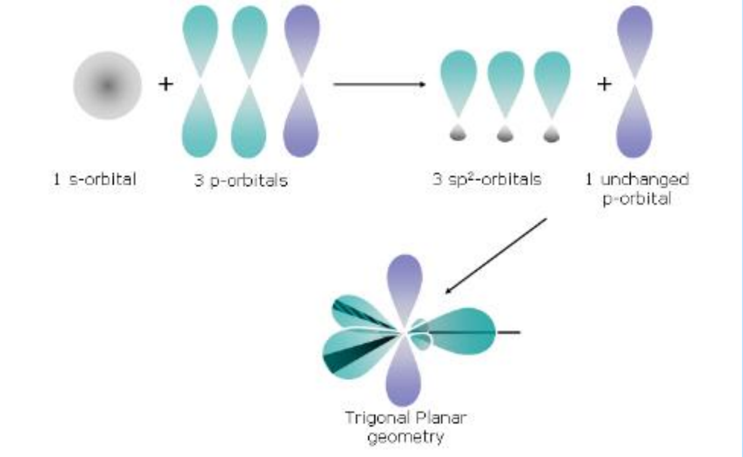
sp^2 hybridization

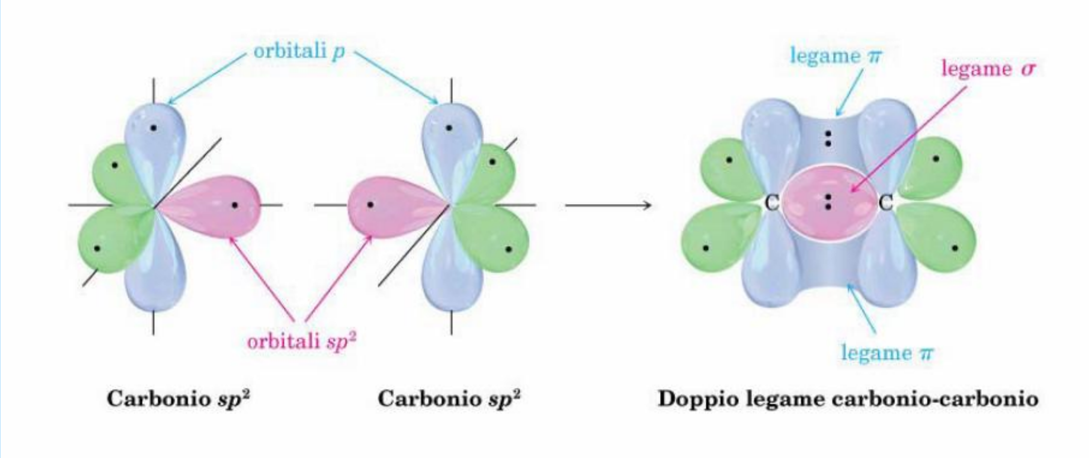




sp^2 hybridization

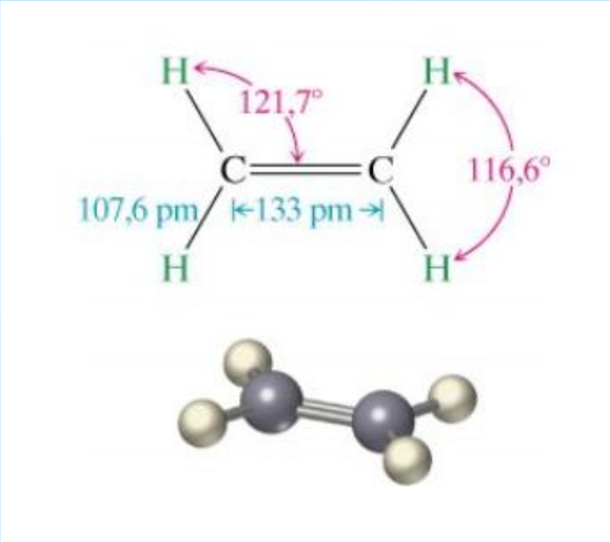


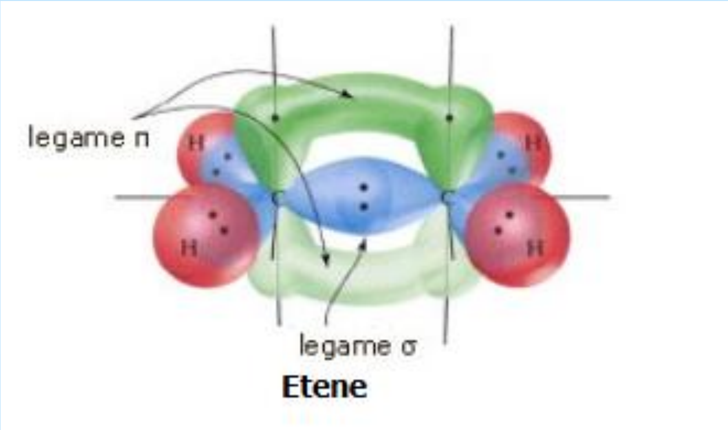


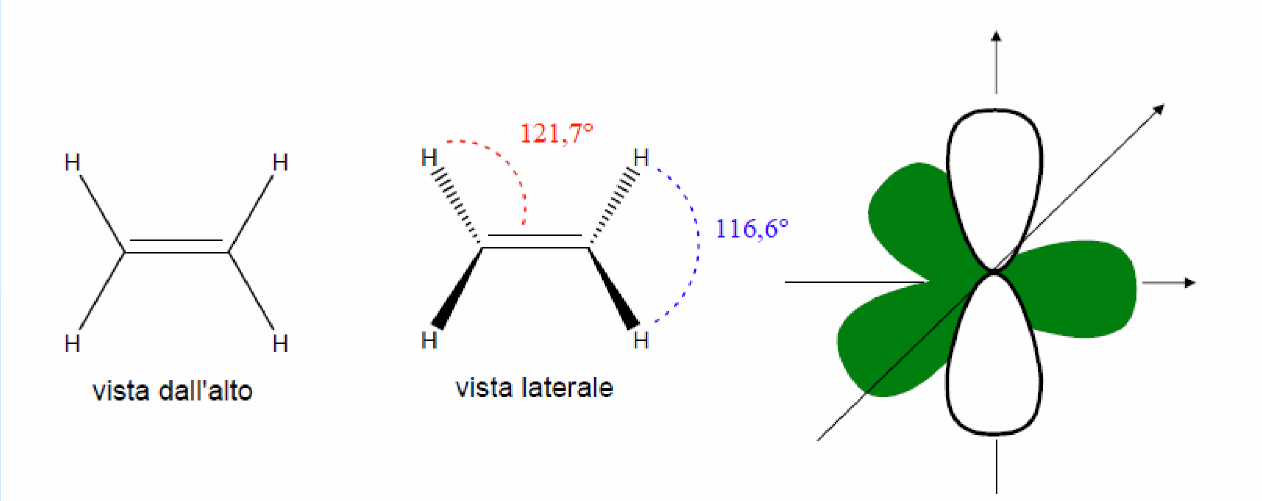


sp^2 hybridization

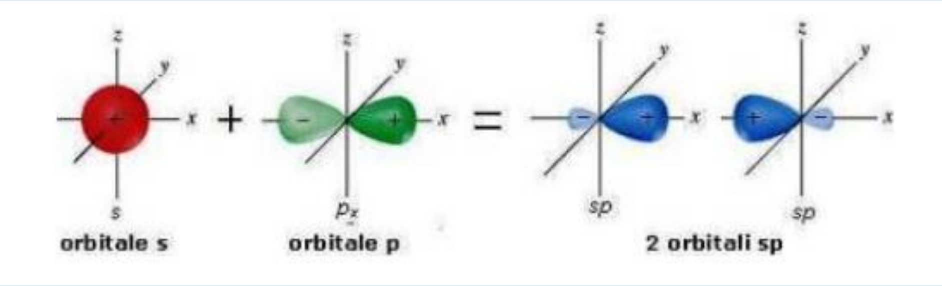
Ethylene

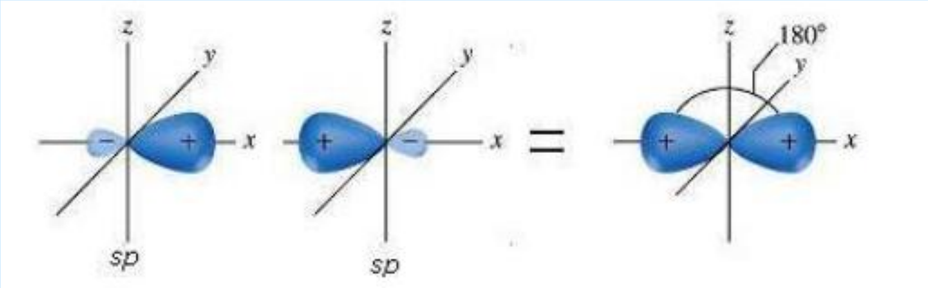


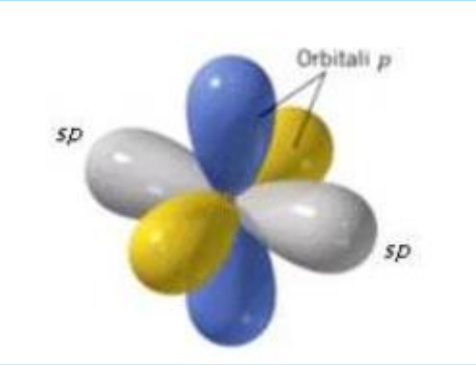


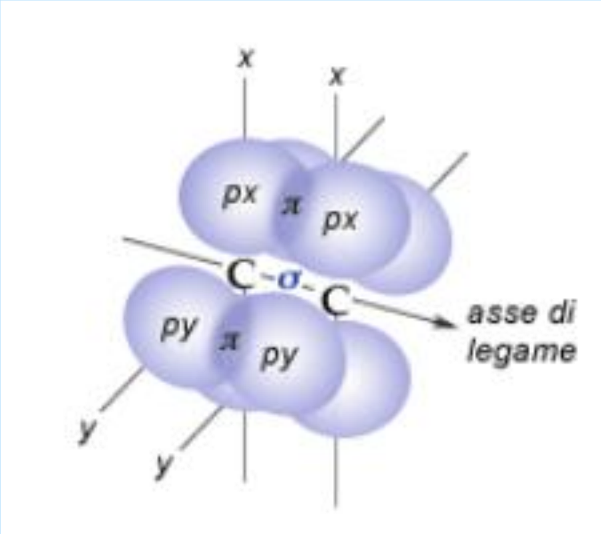


sp hybridization



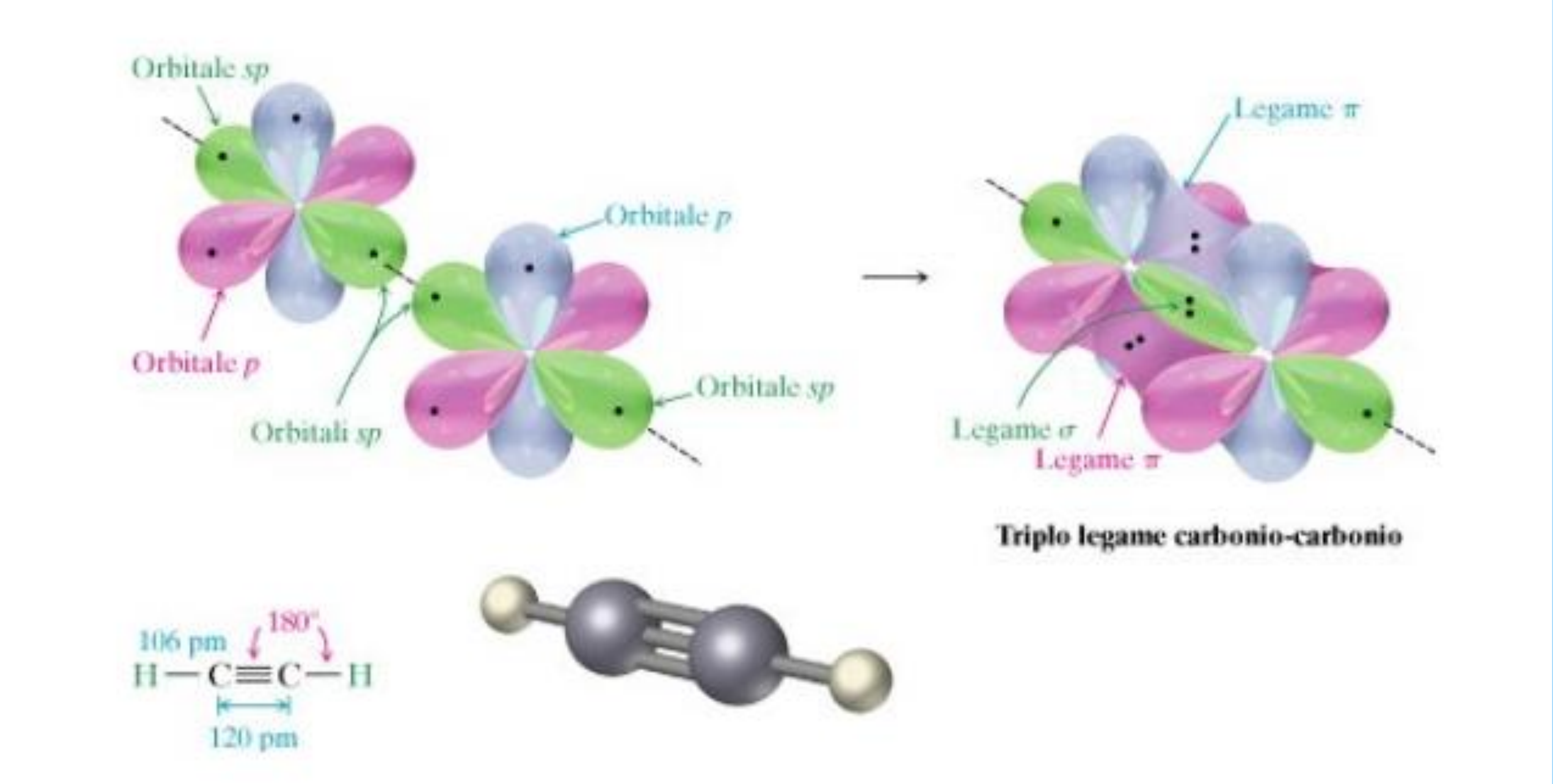




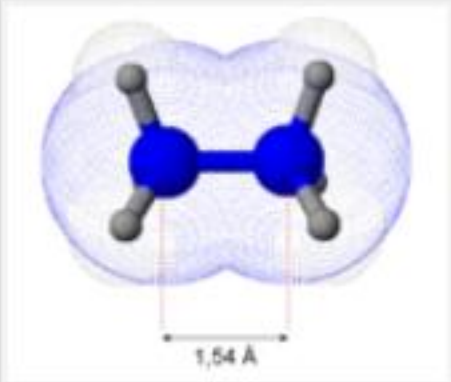
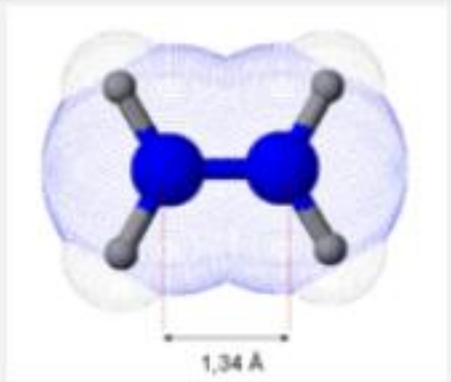
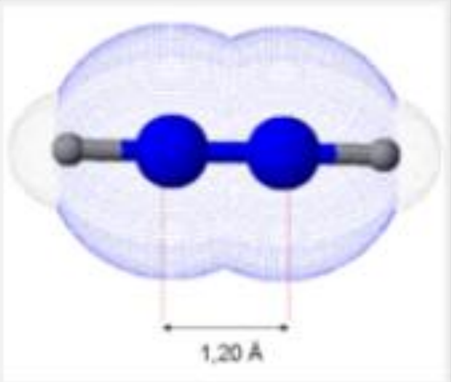


sp hybridization

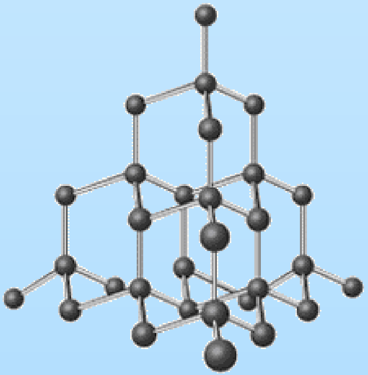
Acetilene

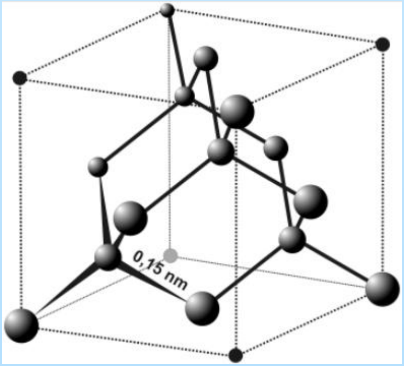


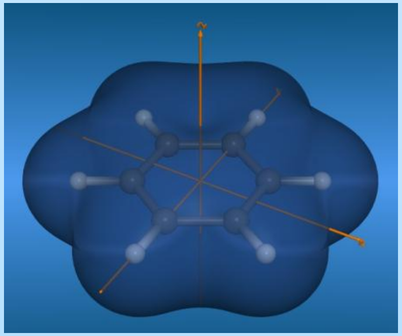
sp^n hybridization

		
1,54 Å	1,34 Å	1,20 Å
Legame singolo Carbonio-Carbonio	Legame doppio Carbonio-Carbonio	Legame triplo Carbonio-Carbonio
Ibridizzazione sp^3	Ibridizzazione sp^2	Ibridizzazione sp

Allotropic states of carbon

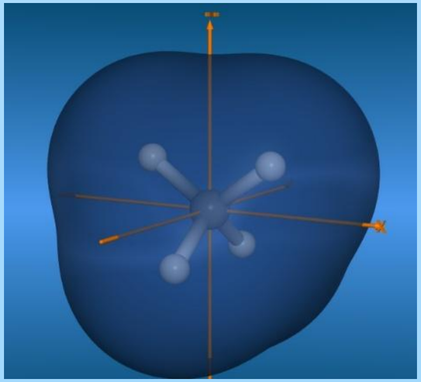


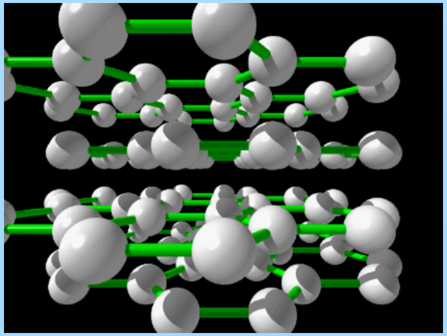


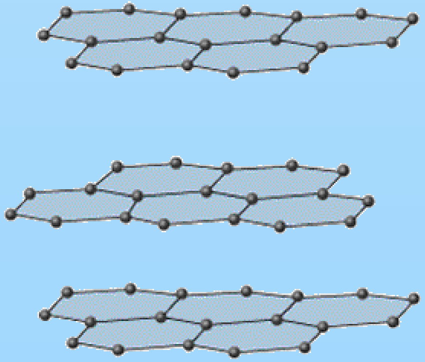


Diamond

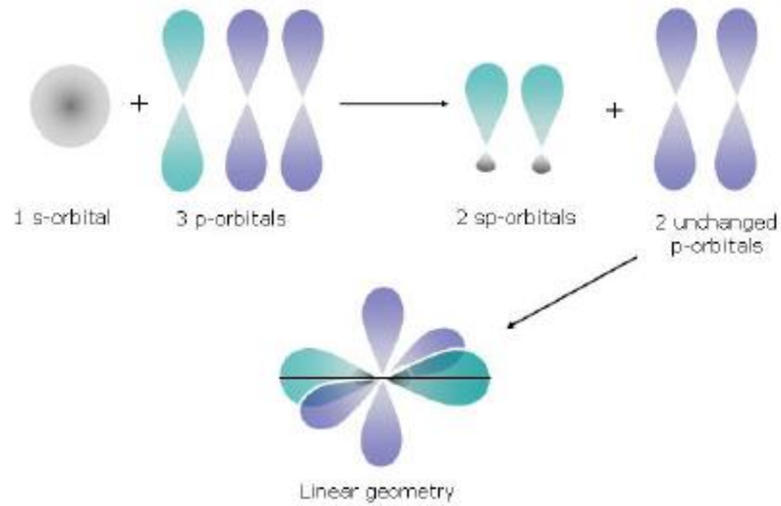
Graphite



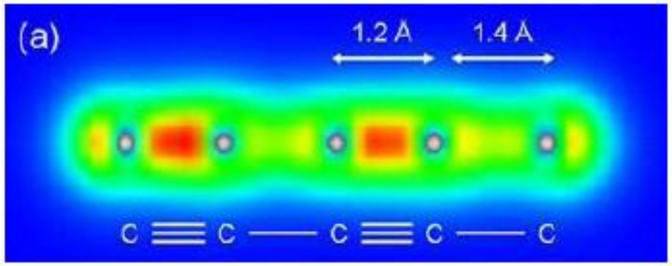


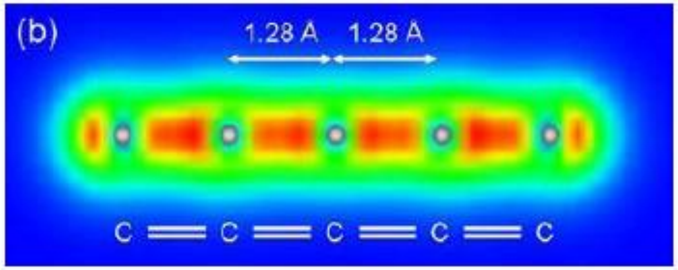


Ibridizzazione *sp*



Due possibilità: (a) ***poliini***, alternanza legami tripli e doppi (b) ***cumuleni***, catena di legami doppi





<u>Problema</u>: i sistemi di carbonio *sp* sono instabili

- reattività delle catene insature (es. O_2);
- tendenza a formare *cross-links* fra le catene, favorendo l'evoluzione verso la più stabile fase sp^2.

Catene *sp* isolate sono state osservate solo in fase gassosa o in matrici di gas inerti a basse temperature.

Chaoite

REPORTS

A New Allotropic Form of Carbon from the Ries Crater

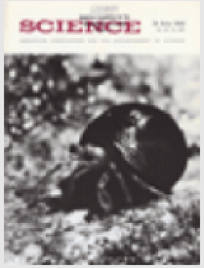
A. El Goresy[1], G. Donnay[1]
+ See all authors and affiliations

Science 26 Jul 1968:
Vol. 161, Issue 3839, pp. 363-364
DOI: 10.1126/science.161.3839.363

Article | Info & Metrics | eLetters | PDF

Abstract

A new allotropic form of carbon occurs in shock-fused graphite gneisses in the Ries Crater, Bavaria. The assemblage in which it occurs consists of hexagonal graphite, rutile, pseudobrookite, magnetite, nickeliferous pyrrhotite, and baddeleyite. Electron-probe analyses indicate that the new phase is pure carbon. It is opaque and much more strongly reflecting than hexagonal graphite. Measurement of x-ray diffraction powder patterns leads to cell dimensions a = 8.948 ± 0.009, c = 14.078 ± 0.017 angstroms, with a primitive hexagonal lattice.



Science
Vol 161, Issue 3839
26 July 1968

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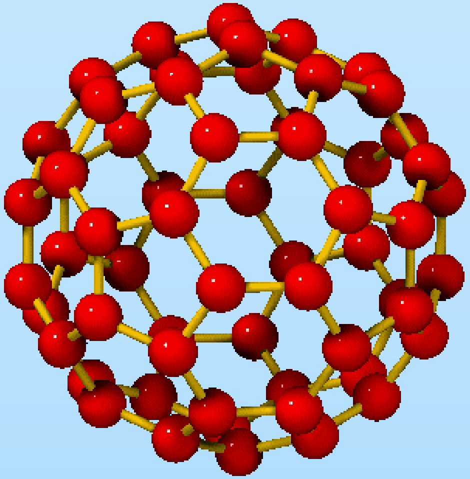
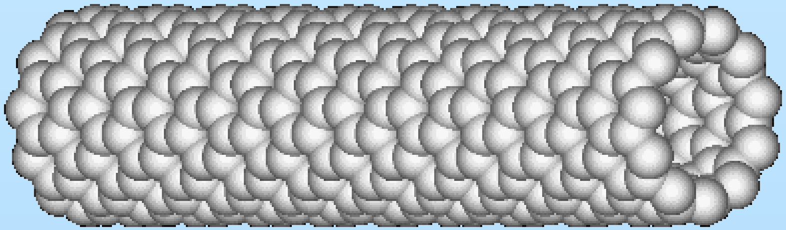
Allotropic states of carbon





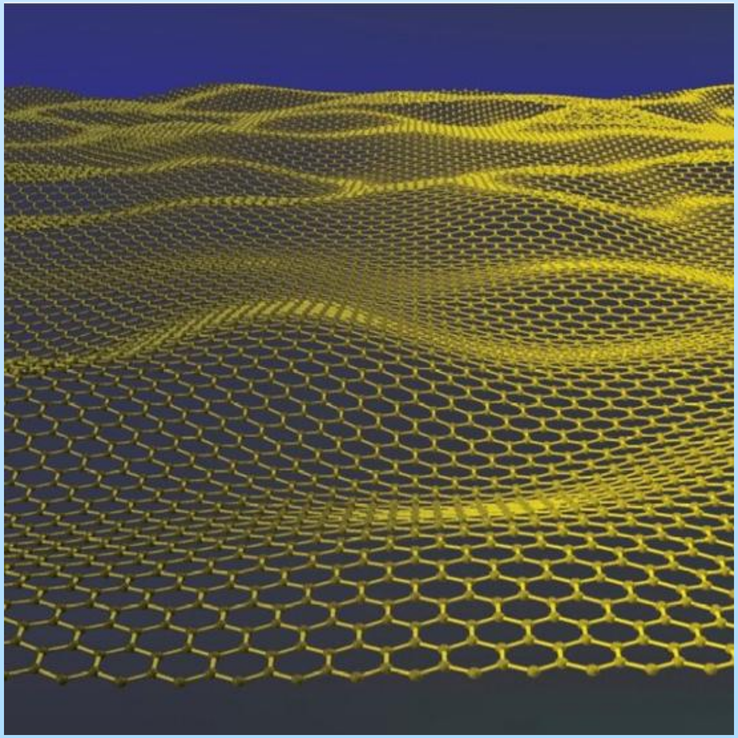
Nanotubi

(Iijima 1991)

Fullerene (C_{60})

Curl, Kroto e Smalley, Nobel Prize in Chemistry 1996

Nanostructures…………………

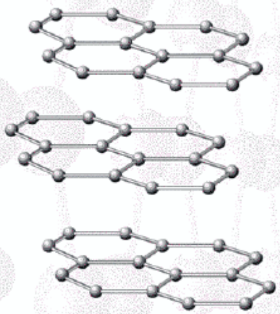
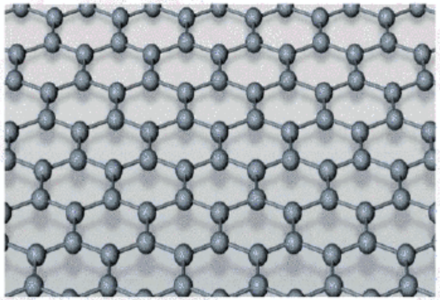
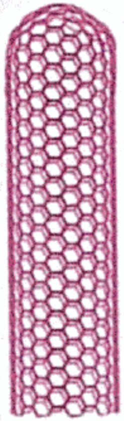
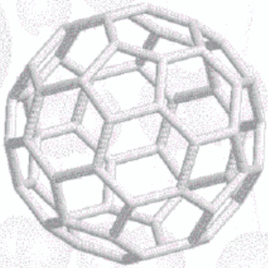


Graphene

K. Novoselov, A. Geim

Nobel Prize in Physics 2010

GRAPHENE ALLOTROPES

3D	2D	1D	0D
			
Graphite	*graphene* PRESUMED NOT TO EXIST IN THE FREE STATE	**Carbon Nanotube** multi-wall: 1952 to *Iijima 1991* single-wall: 1993	**Buckyballs** *Kroto et al 1985*

Diamond ↔ Graphite

Table 2.1

Properties of graphite and diamond

Property	Graphite[a]			Diamond
Lattice structure		Hexagonal		Cubic
Space group		$P6_3/mmc$ (D_{6h}^4)		$Fd3m$ (O_h^7)
Lattice constant[b] (Å)	2.462		6.708	3.567
Atomic density (C atoms/cm^3)		1.14×10^{23}		1.77×10^{23}
Specific gravity (g/cm^3)		2.26		3.515
Specific heat (cal/g·K)		0.17		0.12
Thermal conductivity[b] (W/cm·K)[c]	30		0.06	~25
Binding energy (eV/C atom)		7.4		7.2
Debye temperature (K)	2500		950	1860
Bulk modulus (GPa)		286		42.2
Elastic moduli (GPa)	1060[d]		36.5[d]	107.6[e]
Compressibility (cm^2/dyn)		2.98×10^{-12}		2.26×10^{-13}
Mohs hardness[f]			9	10
Band gap (eV)		−0.04[g]		5.47
Carrier density ($10^{18}/cm^3$ at 4 K)		5		0
Electron mobility[b] (cm^2/Vsec)	20,000		100	1800
Hole mobility[b] (cm^2/Vsec)	15,000		90	1500
Resistivity (Ωcm)	50×10^{-6}		1	$\sim 10^{20}$
Dielectric constant[b] (low ω)	3.0		5.0	5.58
Breakdown field (V/cm)	0			10^7 (highest)
Magnetic susceptibility ($10^{-6} cm^3/g$)	−0.5		-21	—
Refractive index (visible)				2.4
Melting point (K)		4450		4500
Thermal expansion[b] (/K)	-1×10^{-6}		29×10^{-6}	$\sim 1 \times 10^{-6}$
Velocity of sound (cm/sec)	$\sim 2.63 \times 10^5$		$\sim 1 \times 10^5$	$\sim 1.96 \times 10^5$
Highest Raman mode (cm^{-1})	1582			1332

[a] For anisotropic properties, the in-plane (ab plane or a-axis) value is given on the left and the c-axis value on the right.

[b] Measurements at room temperature (300 K).

[c] Highest reported thermal conductivity values are listed.

[d] In-plane elastic constant is C_{11} and c-axis value is C_{33}. Other elastic constants for graphite are $C_{12} = 180$, $C_{13} = 15$, $C_{44} = 4.5$ GPa.

[e] For diamond, there are three elastic constants, $C_{11} = 1040$, $C_{12} = 170$, $C_{44} = 550$ GPa.

[f] A scale based on values from 0 to 10, where 10 is the hardest material (diamond) and 1 is talc [2.8].

[g] A negative band gap implies a band overlap, i.e., semimetallic behavior.

Phase Diagram

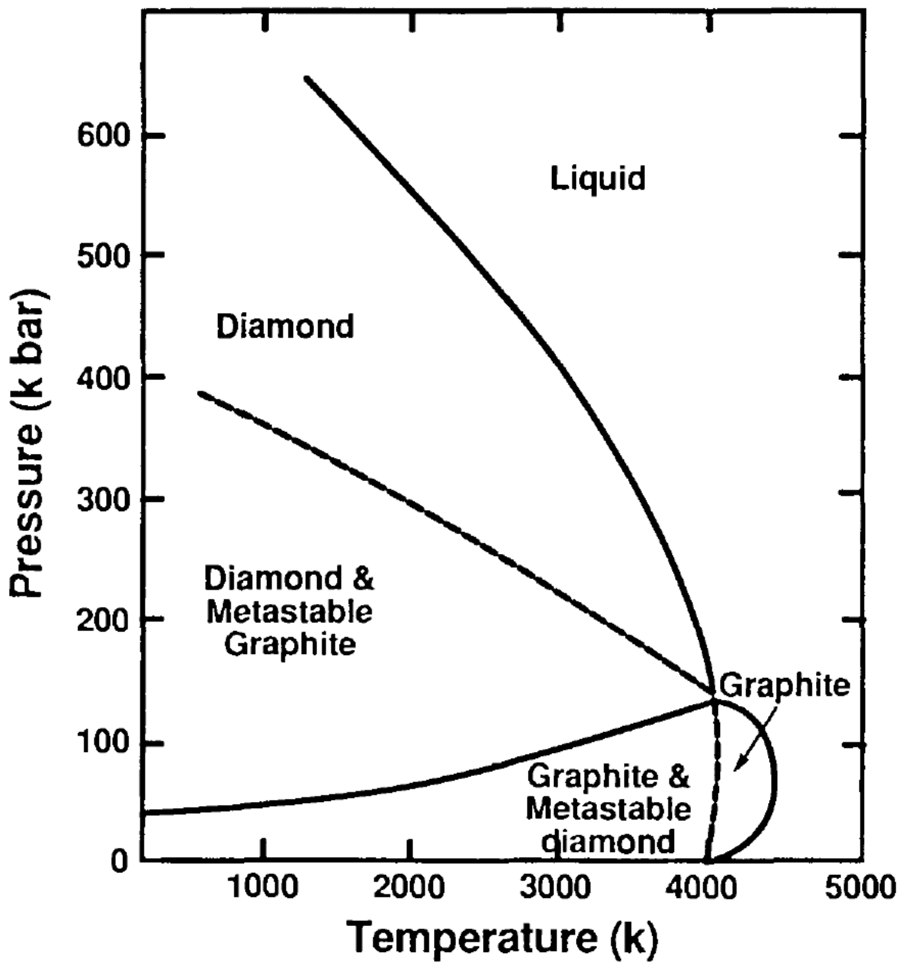
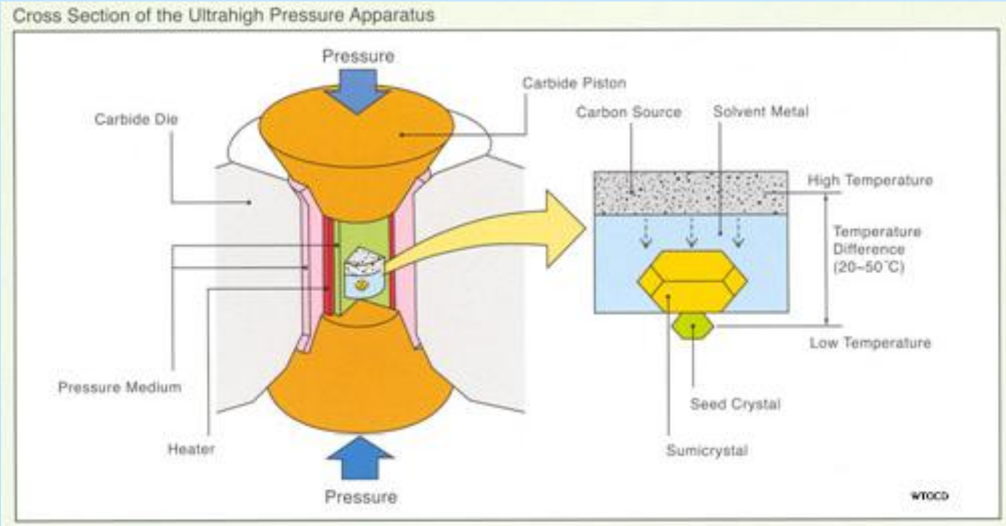


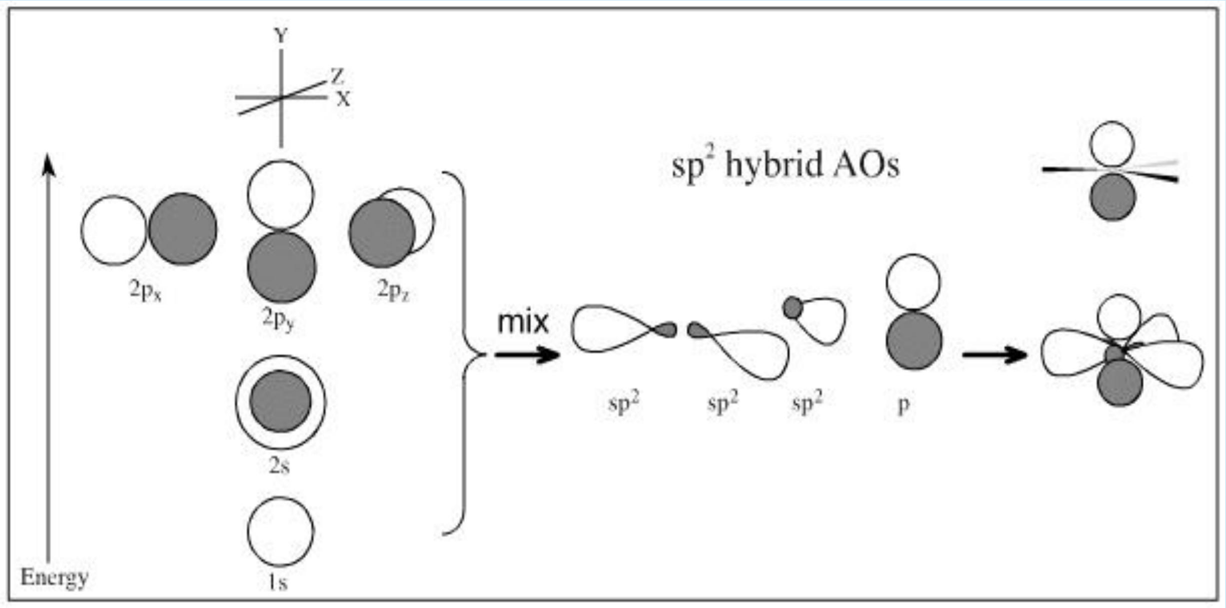
Figure 2.20. Carbon phase diagram.

Diamond synthesis

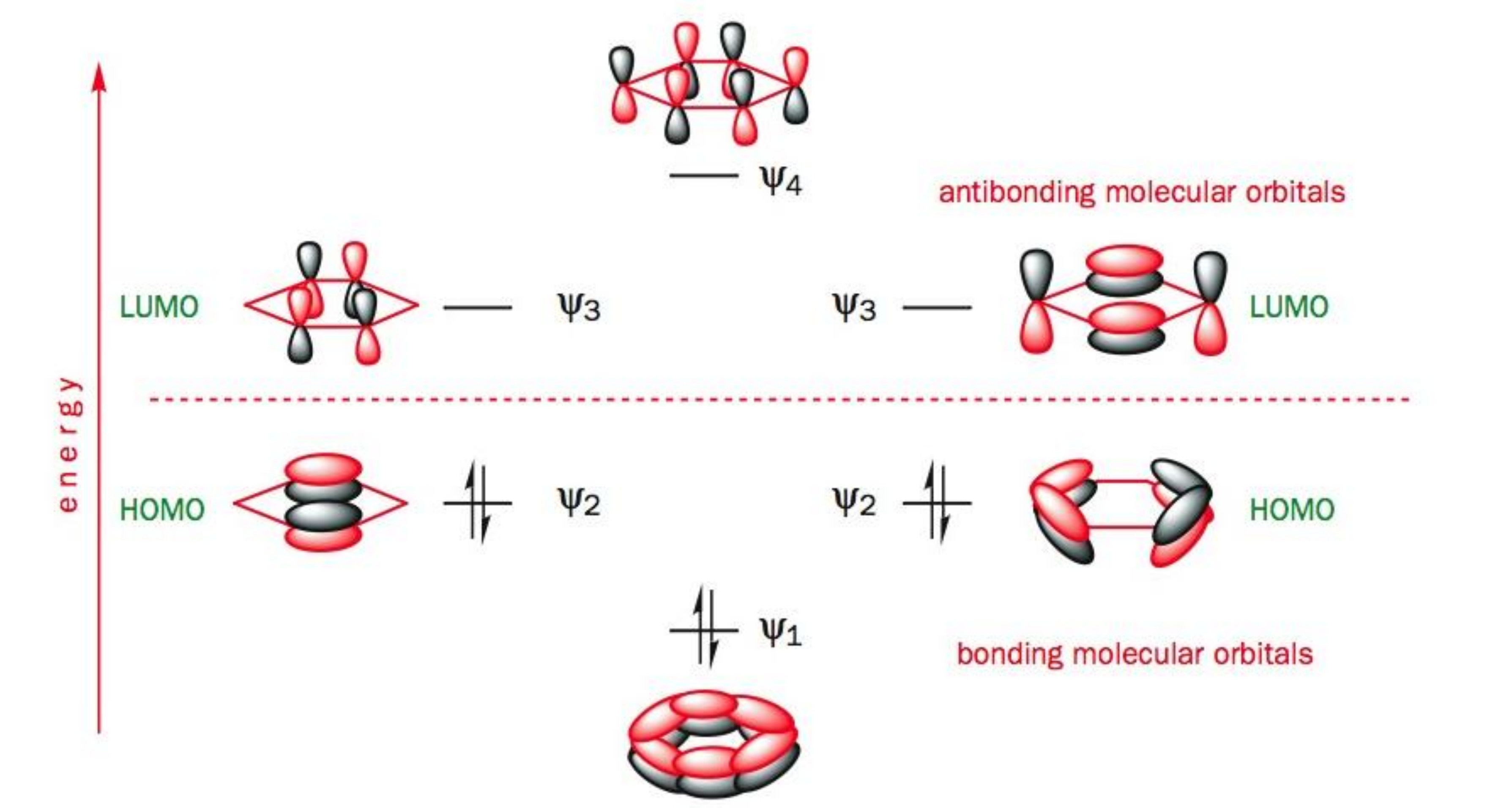


sp^2 hybridization

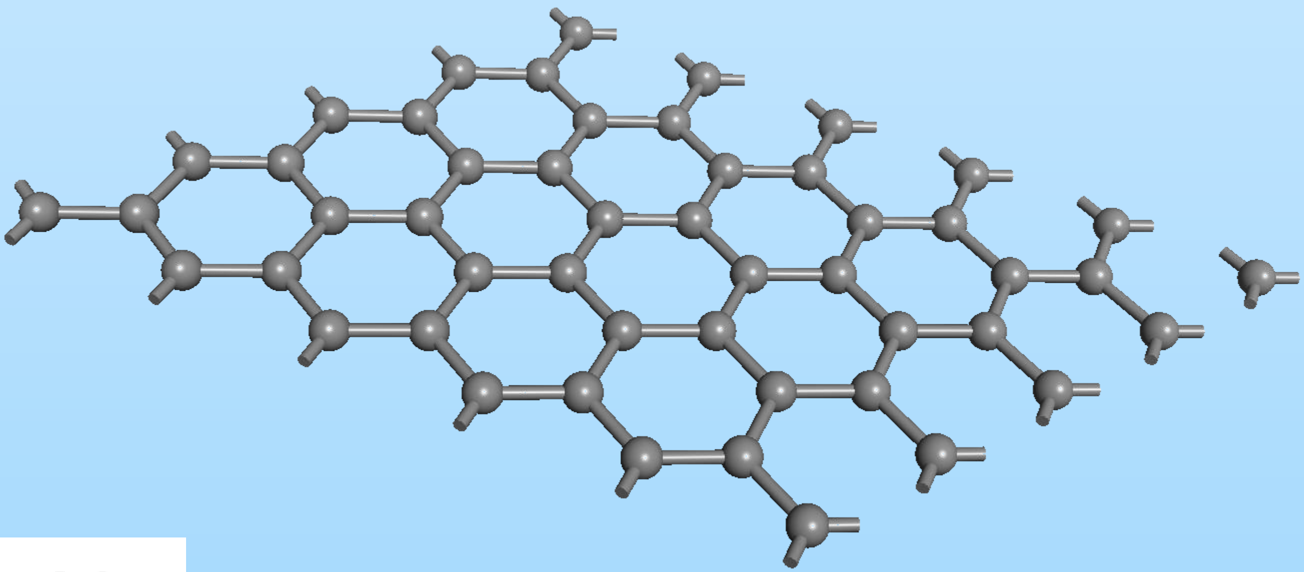
Configuration: [He] $2s^2$ $2p^2$

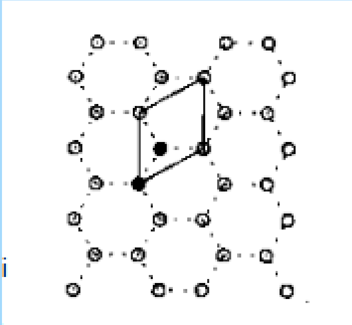


sp^2 hybridization: benzene



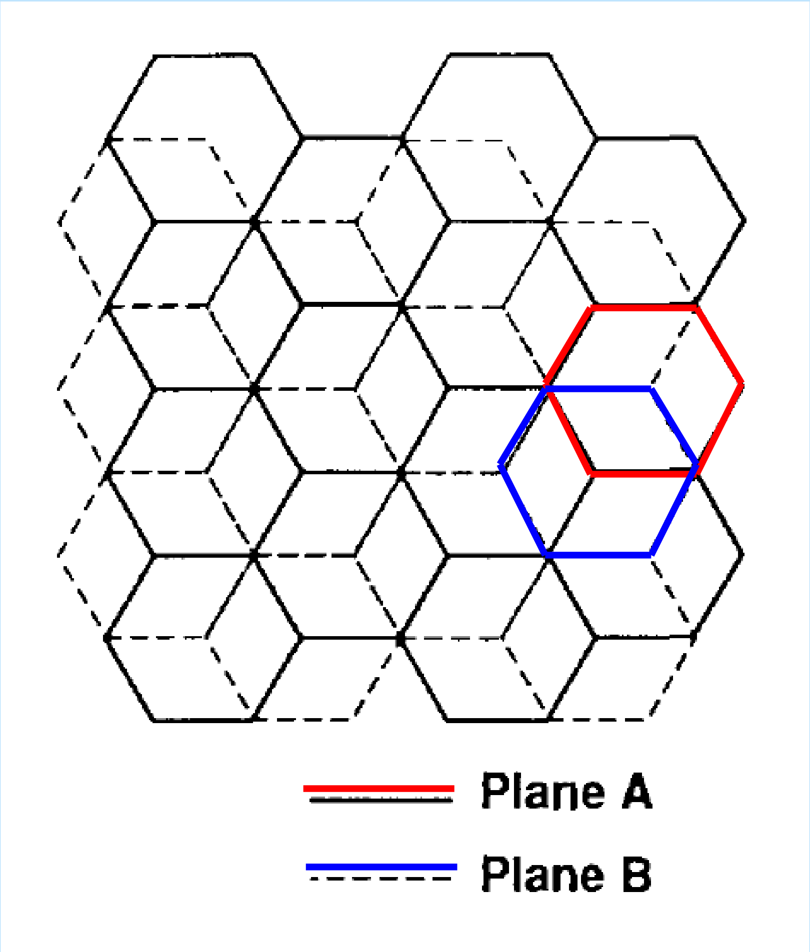
sp^2 hybridization: : graphene



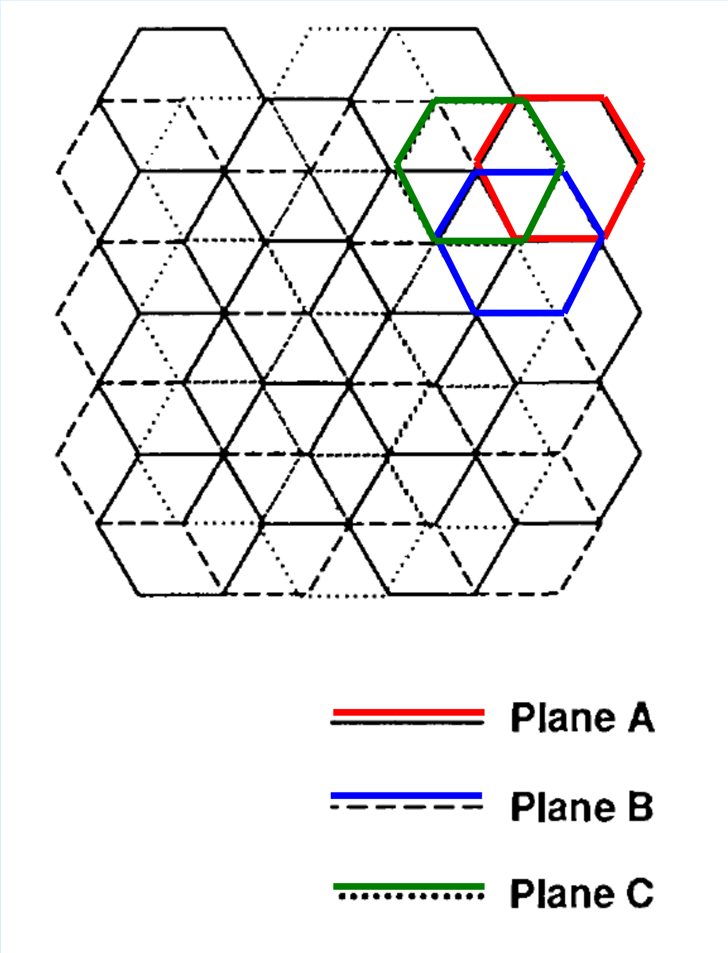


Graphite Structure

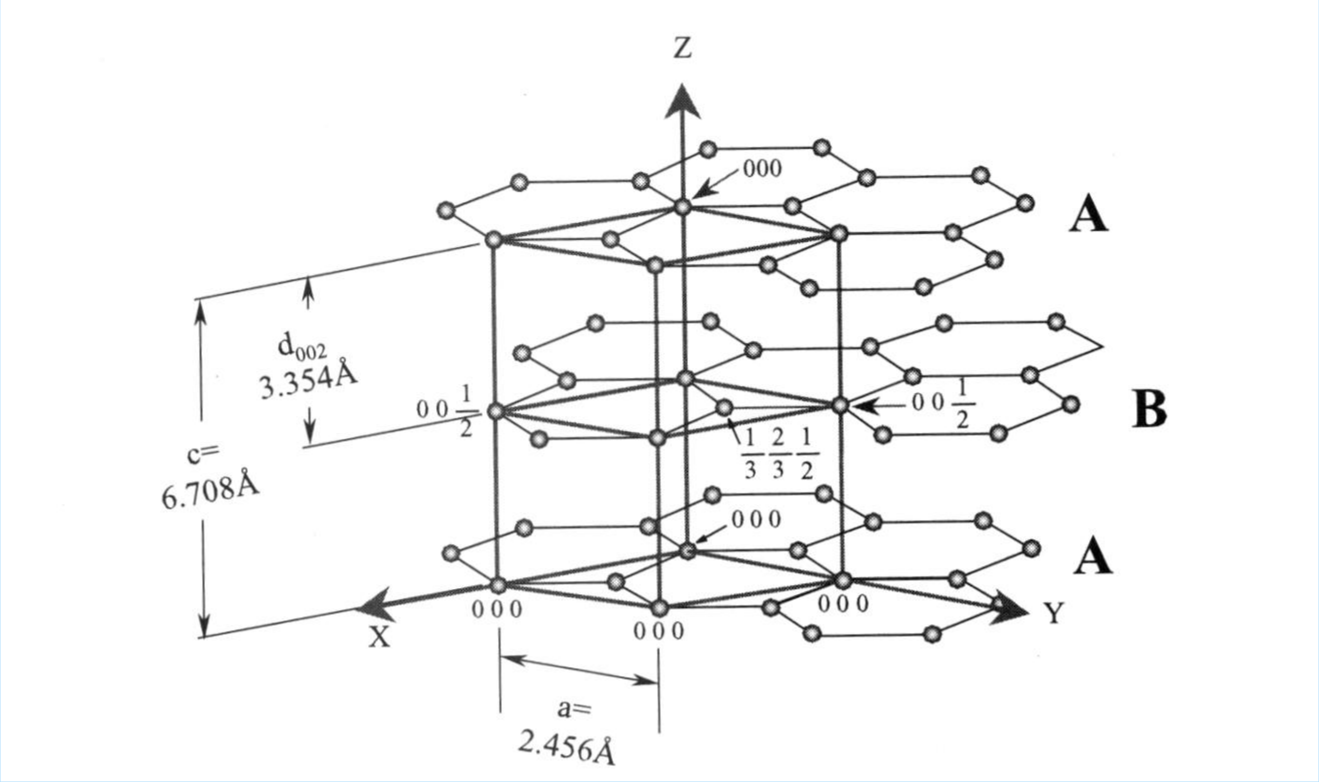
hexagonal graphite



rhombohedral graphite



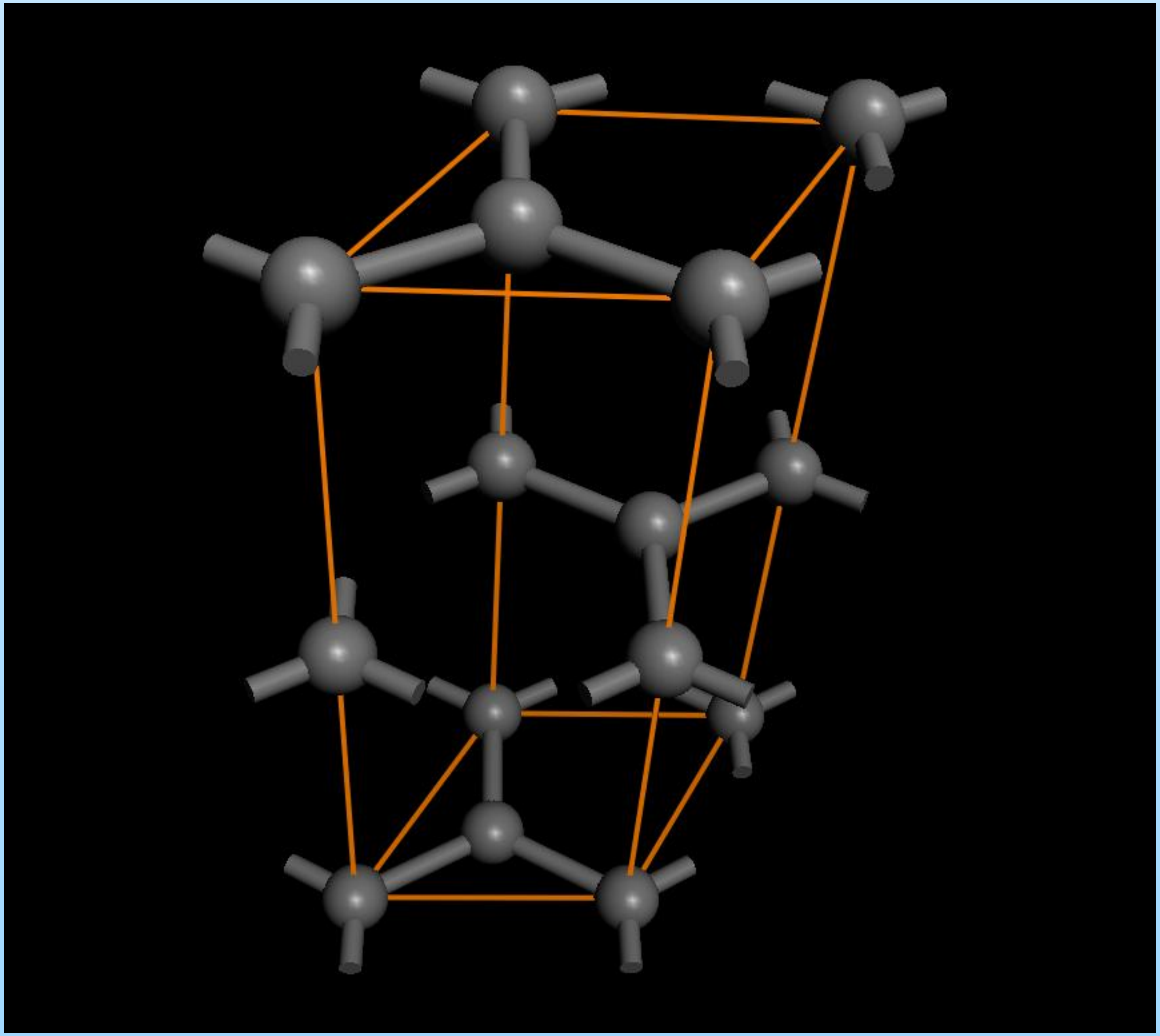
Hexagonal graphite: unit cell



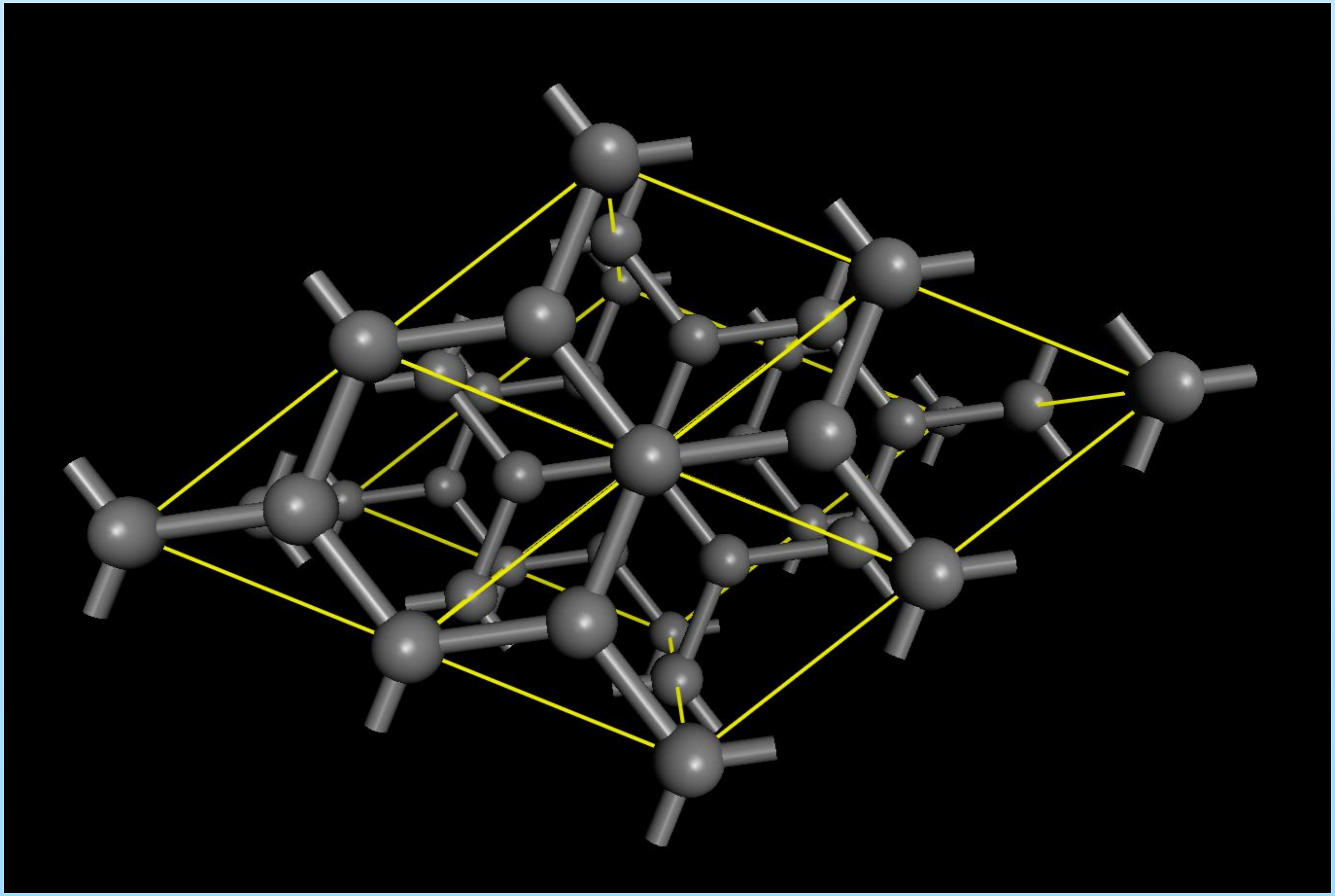
d(C=C) = 1.42 Å

Graphite unit cell

Hexagonal group P 63 MMC #194



Graphite unit cell



2D reciprocal lattice

$$\mathbf{A}=2\pi\frac{\mathbf{b}\times\mathbf{c}}{\mathbf{a}\cdot\mathbf{b}\times\mathbf{c}}\,;\qquad \mathbf{B}=2\pi\frac{\mathbf{c}\times\mathbf{a}}{\mathbf{a}\cdot\mathbf{b}\times\mathbf{c}}\,;\qquad \mathbf{C}=2\pi\frac{\mathbf{a}\times\mathbf{b}}{\mathbf{a}\cdot\mathbf{b}\times\mathbf{c}}\,.$$

EXAMPLE

Reciprocal lattice in two dimensions. A two-dimensional lattice (Fig. 21) has basis vectors a = 2x; b = x + 2y. Find the basis vectors of the reciprocal lattice.

We can use our definitions for the three-dimensional case in this two-dimensional problem if we assume that e is parallel to the z-axis, so the plane of the reciprocal lattice vectors A and B will be in the plane of a and b. Let c=2. Now

$$\mathbf{c}\times\mathbf{a}=\hat{\mathbf{z}}\times(2\hat{\mathbf{x}})=2\hat{\mathbf{y}}\,;$$

$$\mathbf{b}\times\mathbf{c}=\hat{\mathbf{x}}\times\hat{\mathbf{z}}+2\hat{\mathbf{y}}\times\hat{\mathbf{z}}=-\hat{\mathbf{y}}+2\hat{\mathbf{x}}\,;\qquad \mathbf{a}\cdot\mathbf{b}\times\mathbf{c}=4.$$

These results substituted in (33) give

$$\mathbf{A}=\pi\hat{\mathbf{x}}-\tfrac{1}{2}\pi\hat{\mathbf{y}}\,;\qquad \mathbf{B}=\pi\hat{\mathbf{y}},$$

as shown in figure 21.

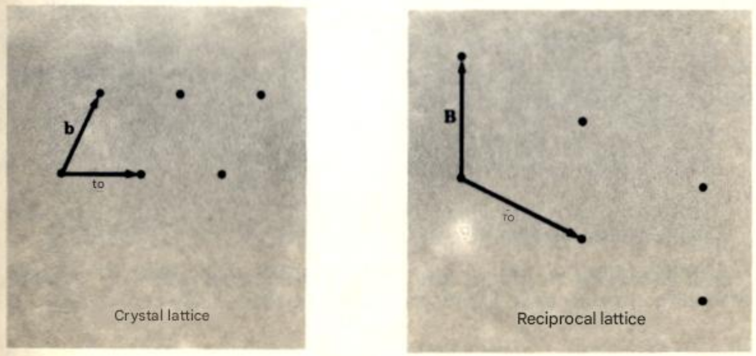
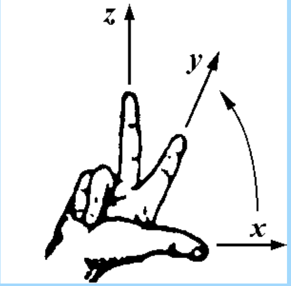


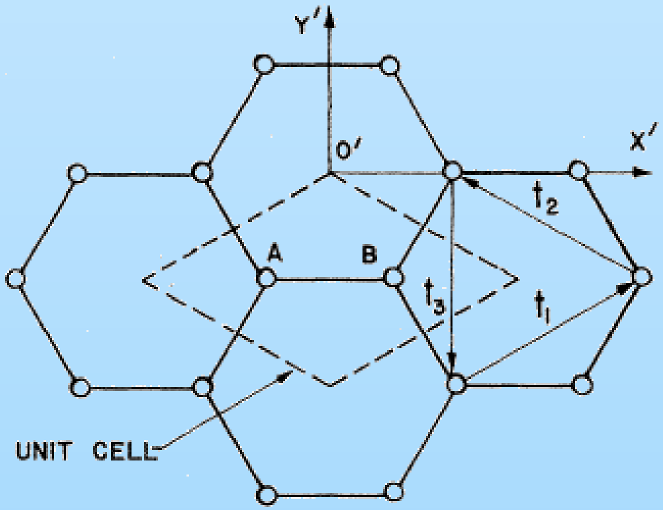
Figure 21 Reciprocal lattice in two dimensions: A and B are perpendicular to groups of planes (lines) in the crystal lattice, that is, to the lines parallel to b and a, respectively. Any vector between points of the reciprocal lattice is perpendicular to some plane in the crystal lattice.

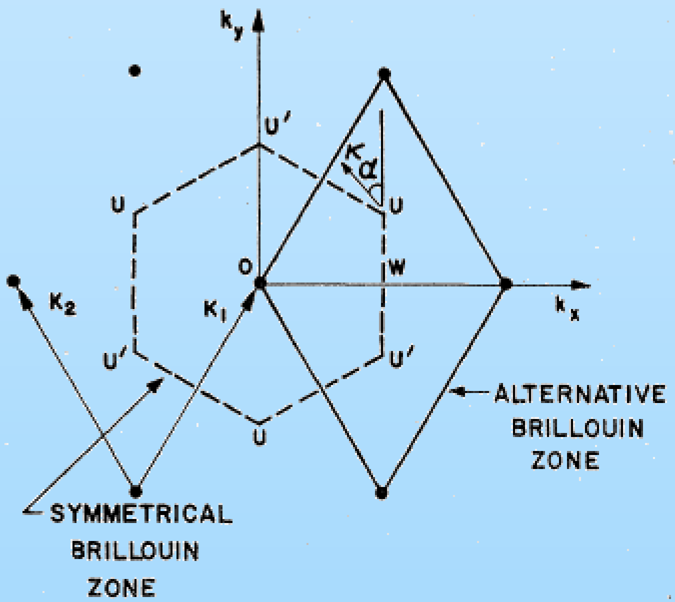


Kittel, Introduzione alla fisica dello Stato Solido

Graphene: unit cell and

Ist Brillouin zone

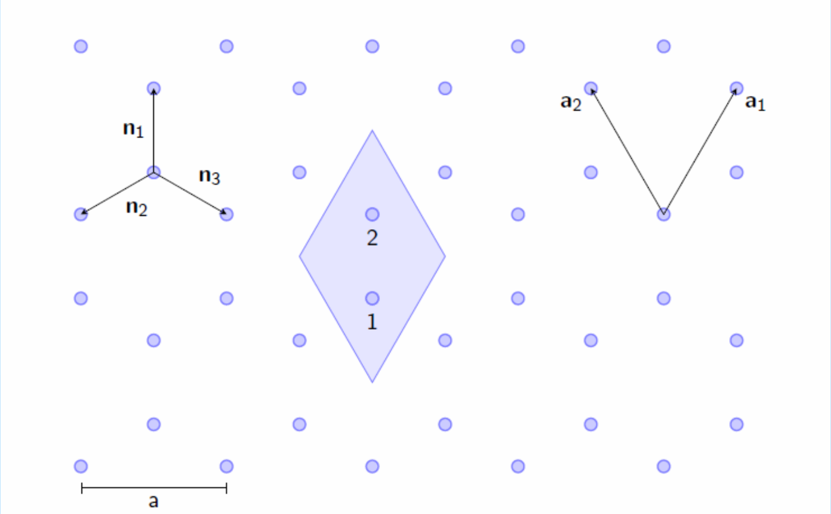


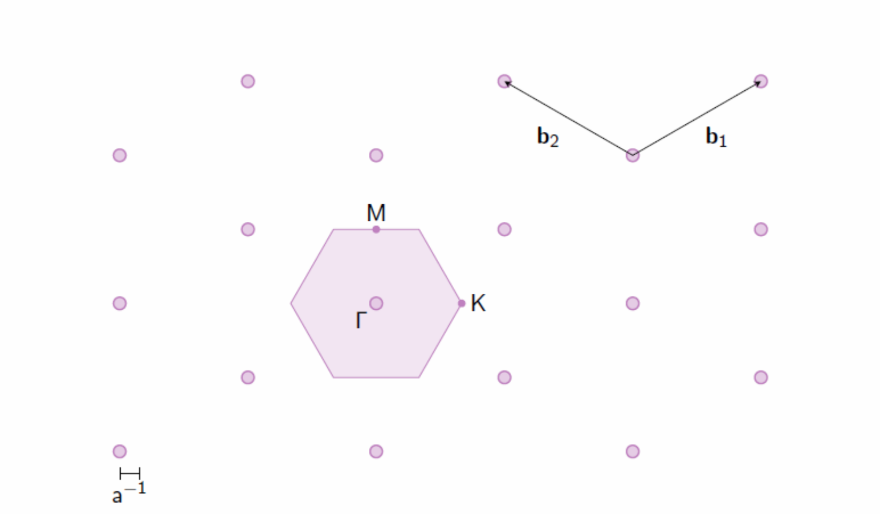


Reciprocal lattice (I B. zone)

Graphene: unit cell and

Ist Brillouin zone





Direct lattice: a_1 e a_2 primitive vectors, n_1, n_2 e n_3 nearest neighbours vectors

Reciprocal lattice: b_1 e b_2 primitive vectors, pink: I B. zone

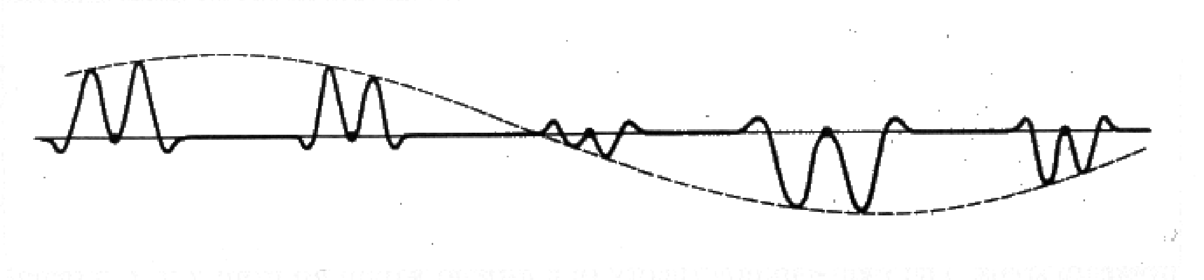
Tight Binding (LCAO)

$$\psi(\mathbf{r}) = \sum_{\mathbf{R}} e^{i\mathbf{k}\cdot\mathbf{R}}\phi(\mathbf{r}-\mathbf{R}),$$

ϕ Wannier functions

ψ n atomic orbitals (denoted by X(r) below)

$$\phi(\mathbf{r}) = \sum_{n} b_n\psi_n(\mathbf{r}).$$



$$\psi(\mathbf{r}+\mathbf{R}) = e^{i\mathbf{k}\cdot\mathbf{R}}\psi(\mathbf{r}).$$

Bloch condition

If the cell includes a basis……

$$\psi_{\mathbf{k}}(\mathbf{r}) = \sum_{j\alpha} c_{j\alpha}\, e^{i\mathbf{k}\mathbf{d}_j} \sum_{\mathbf{R}} e^{i\mathbf{k}\mathbf{R}}\, \phi_{j\alpha}(\mathbf{r}-\mathbf{R}-\mathbf{d}_j),$$

where $\varphi_{j\alpha}(r)$ are the orbitals of a single isolated atom of atomic number Z_j centered at the origin, identified by the index $\alpha \in \{1s, 2s, 2p_x ...\}$. **R** indicates a generic vector of the Bravais lattice, j is an index that identifies the base sites of the crystal, $\mathbf{d}_j$ is the position of the j site within the unitary cell and finally the $c_{j\alpha}$ are the unknown coefficients of the linear combination.

Graphene: Electronic Properties

$$\psi_{2\pi} = \frac{1}{\sqrt{3}}[\psi(2S) + \sqrt{2}\psi(2P_x)]$$

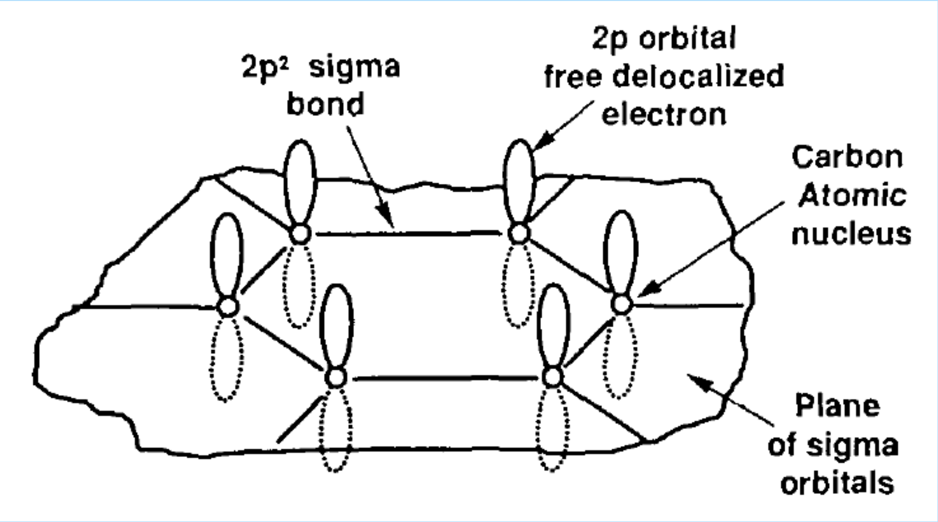
$$\psi_{2\pi/3} = \frac{1}{\sqrt{3}}\left[\psi(2S) - \frac{1}{\sqrt{2}}\psi(2P_x) + \sqrt{(3/2)}\psi(2P_y)\right]$$

$$\psi_{4\pi/3} = \frac{1}{\sqrt{3}}\left[\psi(2S) - \frac{1}{\sqrt{2}}\psi(2P_x) - \sqrt{(3/2)}\psi(2P_y)\right]$$

In plane

P_z out of plane

$$P_z = \frac{1}{2\sqrt{6a^5}} r e^{-\frac{r}{2a}} \sqrt{\frac{3}{8\pi}} \cos\theta$$



X-ray absorption measurements of high resolving power for potassium, which is expected to show wider departure from free electrons, have been carried out by Platt.[16] The K edge investigated shows quite close agreement with his theoretically predicted absorption which was based on the assumption that the electrons are free. No evidence existed to show an energy gap. This, of course, is at best supporting evidence of the non-existence of a gap in potassium since gaps may exist which could be completely masked by the eigenvalue dependence upon wave vector direction.

[16] J. B. Platt, Phys. Rev. 69, 337 (1946).

ACKNOWLEDGMENTS

The authors are indebted to Dr. W. A. Bowers for permission to publish his results on the five additional states shown in Table IV and also wish to thank Dr. Bowers for continuing the application of the method when the war interrupted the work.

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The Band Theory of Graphite

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National Research Council of Canada, Chalk River Laboratory, Chalk River, Ontario

(Received December 19, 1946)

The structure of the electronic energy bands and Brillouin zones for graphite is developed using the "tight binding" approximation. Graphite is found to be a semi-conductor with zero activation energy, i.e., there are no free electrons at zero temperature, but they are created at higher temperatures by excitation to a band contiguous to the highest one which is normally filled. The electrical conductivity is treated with assumptions about the mean free path. It is found to be about 100 times as great parallel to as across crystal planes. A large and anisotropic diamagnetic susceptibility is predicted for the conduction electrons; this is greatest for fields across the layers. The volume optical absorption is accounted for.

1. INTRODUCTION

THE purpose of this paper is to develop a basis for the explanation of some of the physical properties of graphite through the band theory of solids. We shall be concerned primarily with a discussion of its electrical conductivity, but the treatment given makes possible the explanation not only of the electrical conductivity and its anisotropy but also the thermal conductivity, diamagnetic susceptibility, and optical absorption.

The electrical resistivity of single crystals of graphite is about 4 to 6×10^{-5} ohm-cm.[1] This corresponds to a conductivity of the order of that of a poor metal. The temperature coefficient of the conductivity is negative, as in the case of a metal. Polycrystalline graphite, on the other hand, has a much higher resistivity which varies very strongly according to the type of graphite used, and has a *positive* temperature coefficient of conductivity[2] to about 1400°C, and negative thereafter. Since the crystals of commercial graphites tend to be of the order of 10^{-6} cm, and it is quite porous (density ~1.6 as against 2.25 for single crystals), it seems reasonable to attribute the high resistivity of polycrystalline graphite to the crystal boundaries, on which may be lodged impurity atoms. The latter would tend to be driven off on heating, thus accounting for the observed temperature dependence. We shall show, however, that the band theory would seem to make possible the explanation of the conductivity properties of single crystals.

* Now at McGill University.

[1] Given by E. Ryschewitsch, Zeits. f. Elektrochem. ang. physik. Chemie 29, 474 (1923), as $3.9\text{–}6\times10^{-5}$ ohm-cm.

[2] C. A. Hansen, Trans. Am. Electrochem. Soc. 16, 329 (1909) gives 137.5×10^{-5} at 0°C 82.5×10^{-5} at 1400°C.

Tight Binding in graphene

(Wallace 1946)

Phys. Rev. **71** (1947) 622

$$\psi = \varphi_1 + \lambda\varphi_2$$

$$\left.\begin{aligned}\varphi_1 &= \textstyle\sum_A \exp[2\pi i\mathbf{k}\cdot\mathbf{r}_A]X(\mathbf{r}-\mathbf{r}_A)\\ \varphi_2 &= \textstyle\sum_B \exp[2\pi i\mathbf{k}\cdot\mathbf{r}_B]X(\mathbf{r}-\mathbf{r}_B)\end{aligned}\right\}$$

$$\int X(\mathbf{r}-\mathbf{r}_A)X(\mathbf{r}-\mathbf{r}_B)d\tau = 0.$$

No overlap among p^z orbitals

$$H\psi = E\psi$$

$$H_{11} + \lambda H_{12} = ES,$$
$$H_{21} + \lambda H_{22} = \lambda ES,$$

$$\begin{vmatrix} H_{11}-ES & H_{12} \\ H_{21} & H_{22}-ES \end{vmatrix} = 0$$

$$H_{11} = \int \phi_1^* H\phi_1 d\tau, \quad H_{12} = H_{21}^* = \int \phi_1^* H\phi_2 d\tau,$$

$$E = \frac{1}{2S}\{H_{11}+H_{22} \pm ((H_{11}-H_{22})^2 + 4|H_{12}|^2)^{\frac{1}{2}}\}$$

$$H_{22} = \int \phi_2^* H\phi_2 d\tau$$

$$S = \int \phi_1^*\phi_1 d\tau = \int \phi_2^*\phi_2 d\tau. \quad = N \text{ (celle nel cr.)}$$

Graphene: Electronic Properties

$H_{11} = H_{22}$ By symmetry

$$H_{11}' = H_{22}' = \frac{1}{N} H_{11} = \frac{1}{N} H_{22},$$

$$H_{12}' = \frac{1}{N} H_{12}$$

$$E = H_{11}' \pm |H_{12}'|.$$

+ out, - in the hexagonal B. zone

$$\Delta E = 2|H_{12}'|$$

$$H_{11}' = \frac{1}{N} \sum_{A,A'} \exp[-2\pi i \mathbf{k} \cdot (\mathbf{r}_A - \mathbf{r}_{A'})] \times \int X^*(\mathbf{r} - \mathbf{r}_A) H X(\mathbf{r} - \mathbf{r}_{A'}) d\tau.$$

putting

$$E_0 = \int X^*(\mathbf{r}) H X(\mathbf{r}) d\tau,$$

$$\gamma_0' = -\int X^*(\mathbf{r} - \boldsymbol{\varrho}') H X(\mathbf{r}) d\tau,$$

$\boldsymbol{\varrho}' = \mathbf{a}_1$ Vector connecting nearest neighbors A

$$H_{11}' = E_0 - 2\gamma_0' (\cos 2\pi k_y a + 2 \cos \pi k_x a\sqrt{3} \cos \pi k_y a)$$

Graphene: Electronic Properties

$$H = H_0 + (H - H_0)$$

H_0 Hamiltonian of an isolated C atom

$$H - H_0 = V - U < 0$$

V Periodic lattice potential
U Potential of a C atom

$$H_0 X = E_0 X$$

$$E_0 = \bar{E} - \int X^*(\mathbf{r})(U - V)X(\mathbf{r})d\tau$$

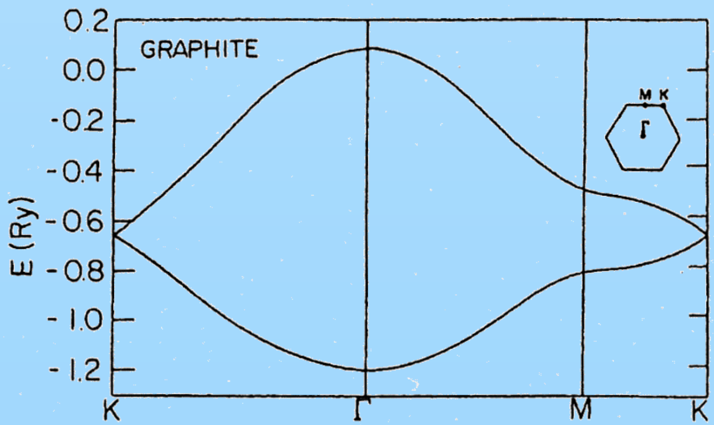
$$\gamma_0' = \int X^*(\mathbf{r} - \boldsymbol{\varrho}')(U - V)X(\mathbf{r})d\tau > 0$$

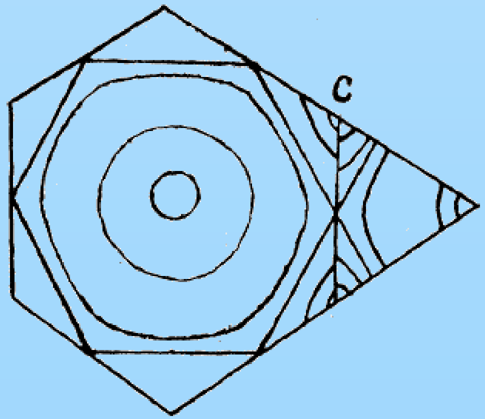
$$\gamma_0 = \int X^*(\mathbf{r} - \boldsymbol{\varrho})(U - V)X(\mathbf{r})d\tau > 0$$

$\boldsymbol{\varrho} = \mathbf{AB}$ Contiguous lattices

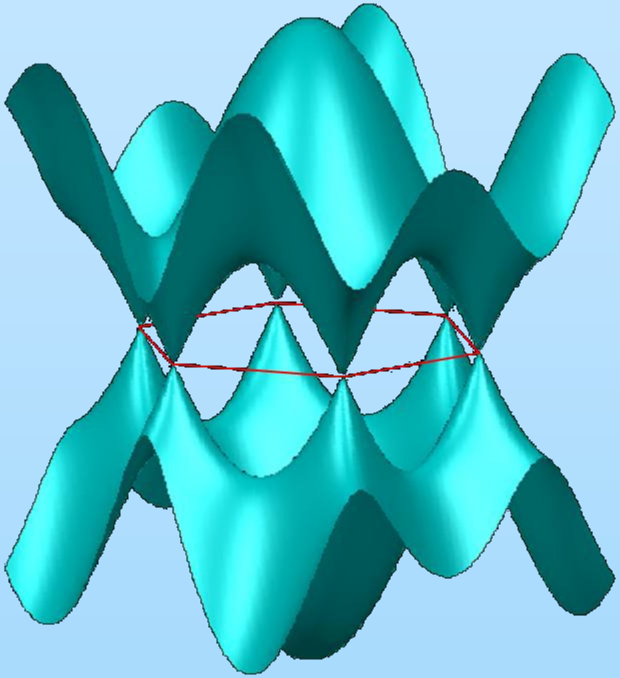
$$H_{12}' = -\gamma_0(\exp[-2\pi i k_x(a/\sqrt{3})] + 2\cos\pi k_y a \cdot \exp[2\pi i k_x(a/2\sqrt{3})]),$$

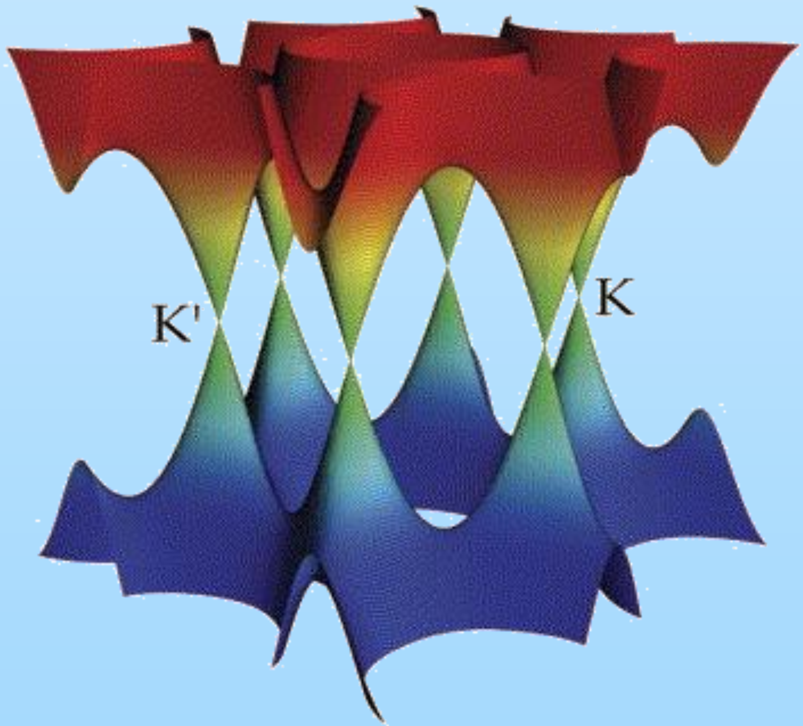
$$|H_{12}|^2 = \gamma_0^2(1 + 4\cos^2\pi k_y a + 4\cos\pi k_y a \cos\pi k_x \sqrt{3}a)$$



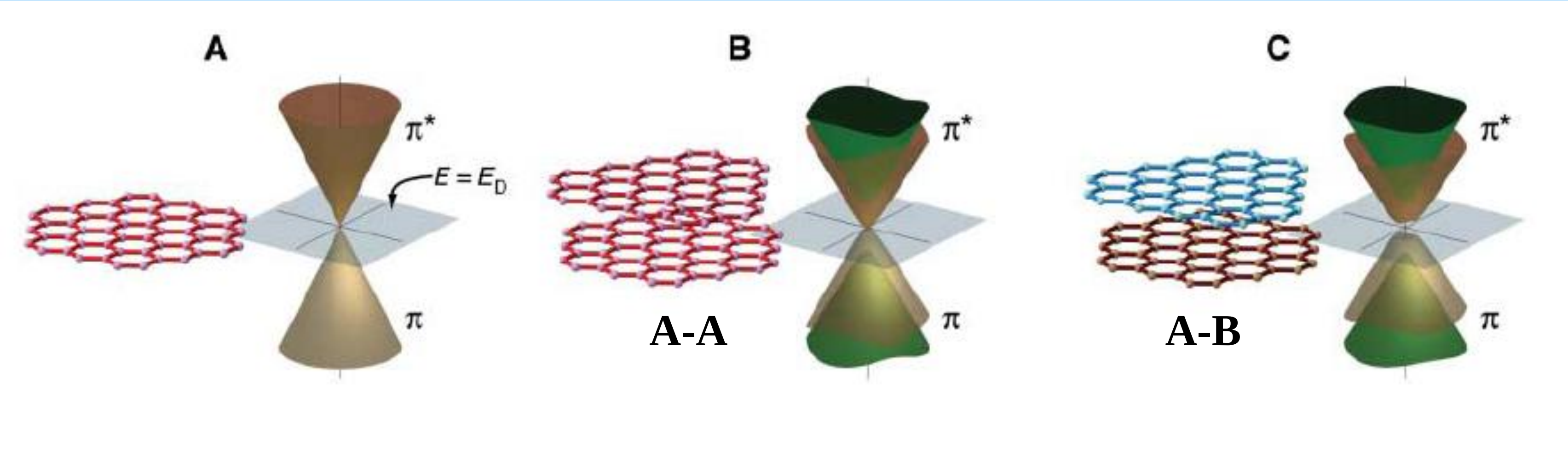


Graphene: Electronic Properties





Multigraphene (2 layers)



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Robust superconductivity in magic-angle multilayer graphene family

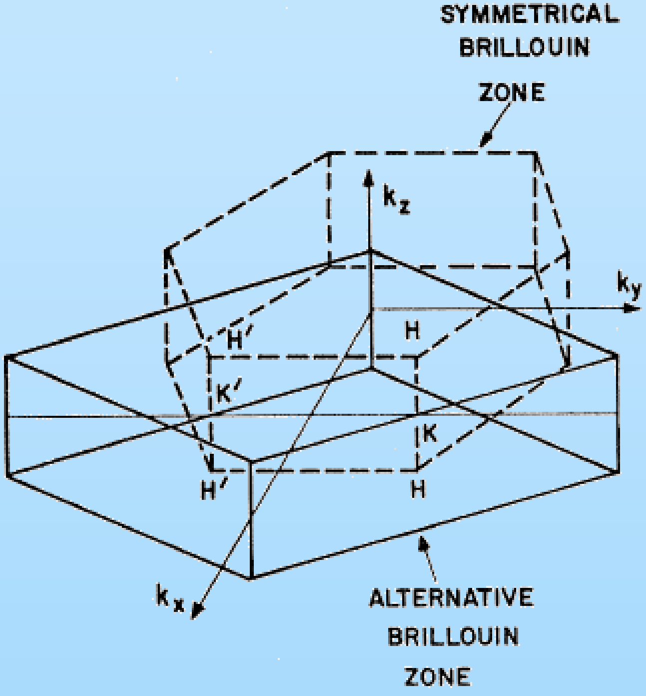
Jeong Min Park[1,3] ✉, Yuan Cao[1,3], Li-Qiao Xia[1], Shuwen Sun[1], Kenji Watanabe[2], Takashi Taniguchi[2] and Pablo Jarillo-Herrero[1] ✉

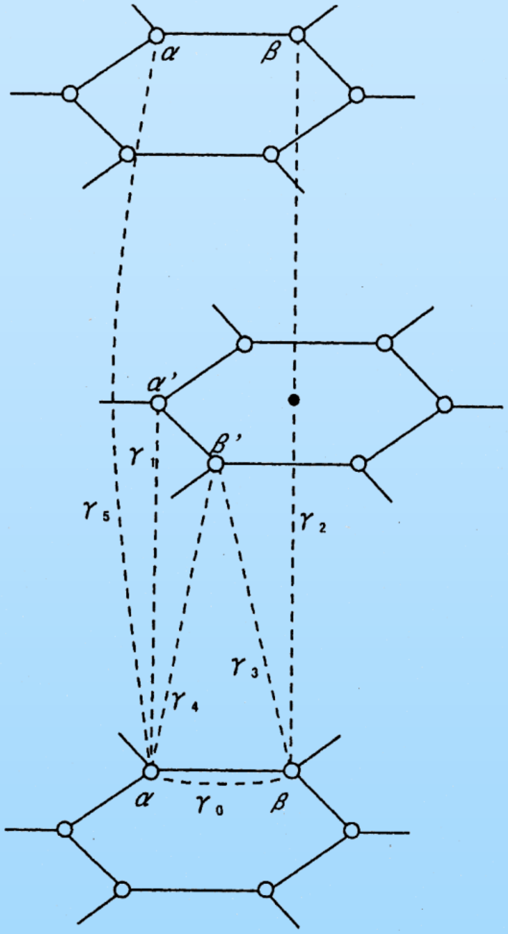
The discovery of correlated states and superconductivity in magic-angle twisted bilayer graphene (MATBG) established a new platform to explore interaction-driven and topological phenomena. However, despite multitudes of correlated phases observed in moiré systems, robust superconductivity appears the least common, found only in MATBG and more recently in magic-angle twisted trilayer graphene. Here we report the experimental realization of superconducting magic-angle twisted four-layer and five-layer graphene, hence establishing alternating twist magic-angle multilayer graphene as a robust family of moiré superconductors. This finding suggests that the flat bands shared by the members play a central role in the superconductivity. Our measurements in parallel magnetic fields, in particular the investigation of Pauli limit violation and spontaneous rotational symmetry breaking, reveal a clear distinction between the $N=2$ and $N>2$-layer structures, consistent with the difference between their orbital responses to magnetic fields. Our results expand the emergent family of moiré superconductors, providing new insight with potential implications for design of new superconducting materials platforms.

Moiré quantum matter results from stacking two or more atomically thin materials with a lattice mismatch or at a relative twist angle[1]. Motivated by the discovery of magic-angle twisted bilayer graphene (MATBG)[2,3], in the past few years moiré systems with different types of constituent layers and structures have been created, hosting a number of correlated and topological states. Phenomena including but not limited to correlated insulators, quantum anomalous Hall effect, ferromagnetism, and generalized Wigner crystals have been discovered and reproduced in various new moiré systems[4–19]. However, for the first few years robust and reproducible moiré superconductivity was seen only in MATBG[3,20,21], despite reports of signatures of superconductivity in a few other systems[5,6,8,9,11,15,22,23].

studied, providing insights into the nature of the correlated states, non-trivial topology and superconductivity[2,3,20,21,30–36]. It has been theoretically shown[37] that for three or more twisted layers of graphene, there are similar series of 'magic' angles if the layers are alternatively twisted by $(\theta, -\theta, \theta, \ldots)$ (Fig. 1a). The values of such angles can be analytically computed from the bilayer value in the chiral limit, where the interlayer hopping at AA sites is turned off[37]. As illustrated in Fig. 1b, they are in fact elegantly related by simple trigonometric transformations, that is the largest magic angle can be expressed as $\theta_N = \theta_\infty \cos\frac{\pi}{N+1}$, where N is the number of layers and $\theta_\infty = 2\theta_{N=2}$ is the asymptotic limit of the largest magic angle as $N \to \infty$. As N increases, the magic angle increases and the moiré length scale decreases. The real magic-angle values deviate slightly

Graphite: electronic properties

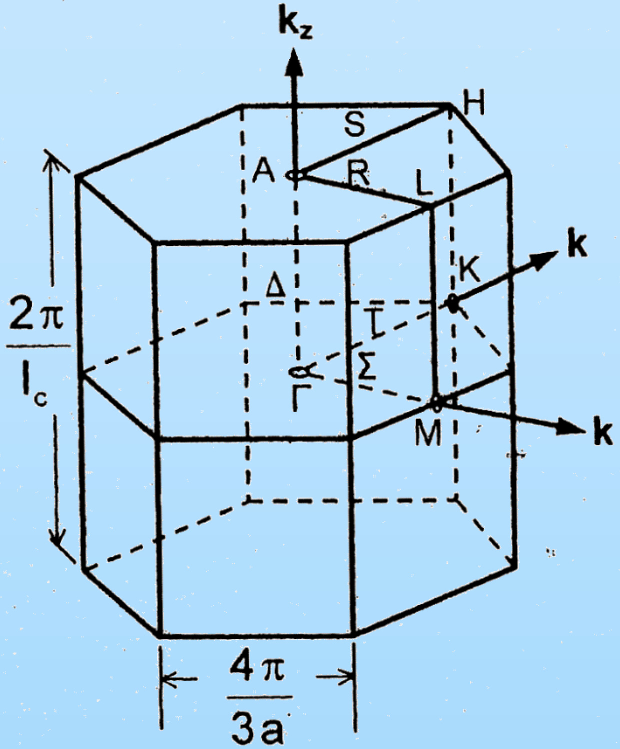




$\gamma_0 >> \gamma_n$

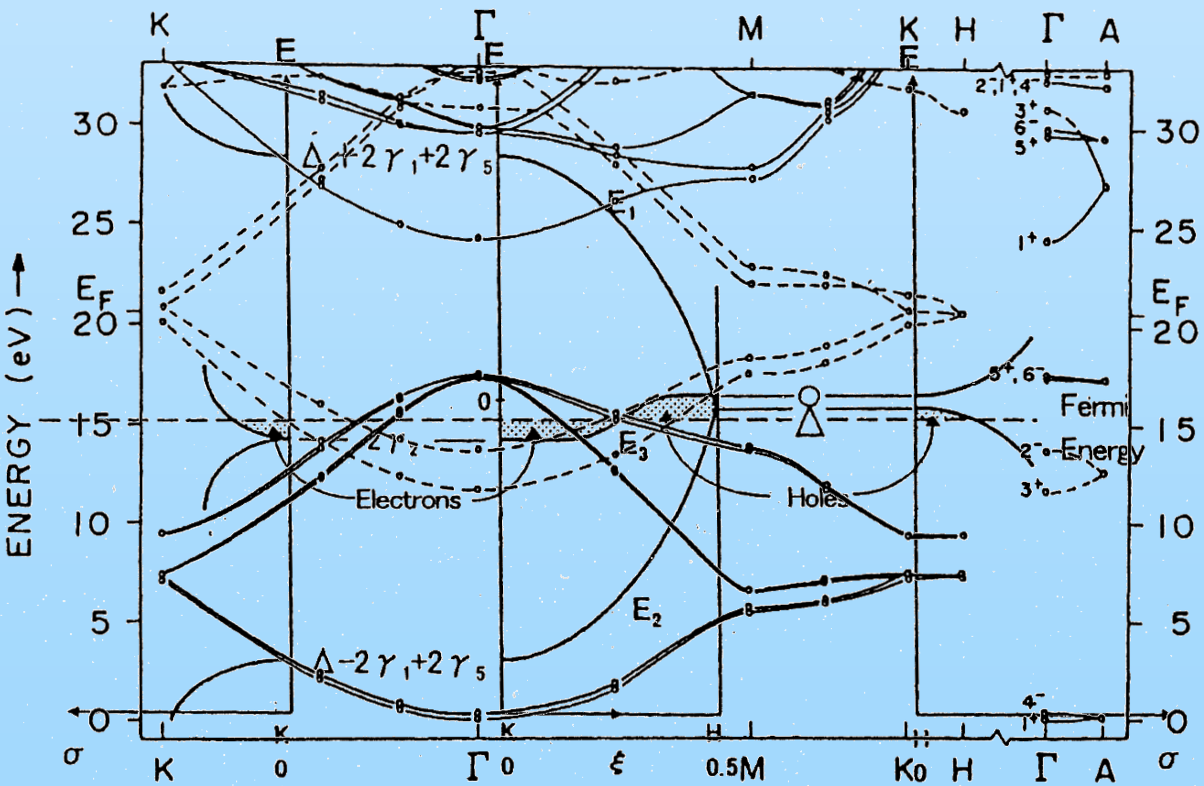
$\gamma_0 = 3.16,\ \gamma_1 = 0.39,$
$\gamma_2 = -0.020,\ \gamma_3 = 0.315,\ \gamma_4 \simeq 0.044,$
$\gamma_5 = 0.038;\ \Delta = -0.008$ eV

Graphite: electronic properties

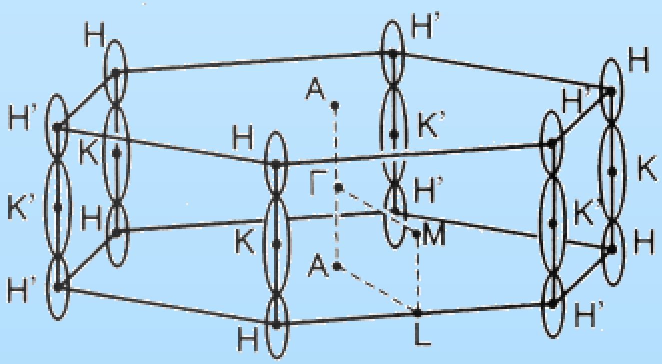


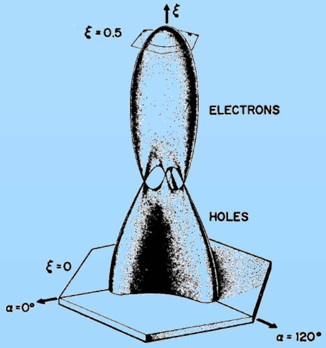
$\gamma_0 = 3.16$, $\gamma_1 = 0.39$,
$\gamma_2 = -0.020$, $\gamma_3 = 0.315$, $\gamma_4 \simeq 0.044$,
$\gamma_5 = 0.038$; $\Delta = -0.008$ eV

4 bande (tratteggiate)

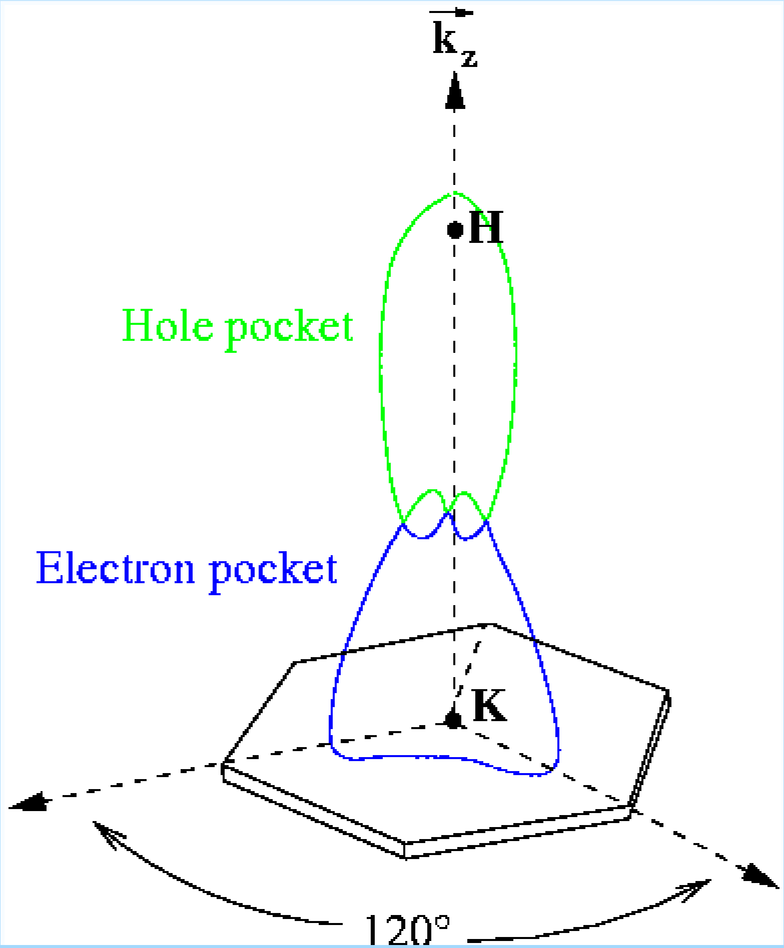


Graphite: Fermi surface





Dresselhaus 1964



Graphite: Fermi surface

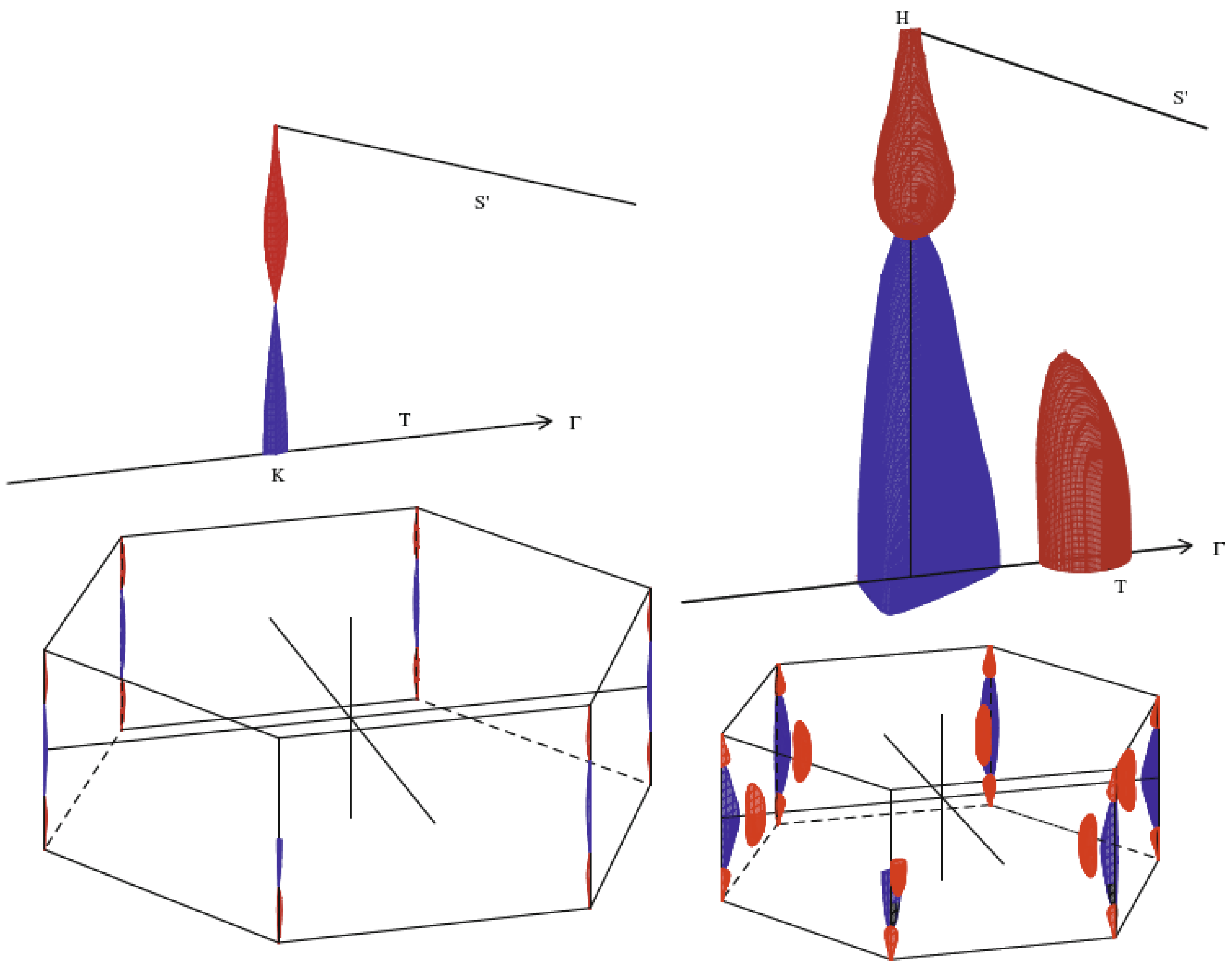


Fig. 4. Fermi surface $p=0$ (left) and 50 GPa (right).