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STRUCTURES OF GASES CHEMISORBED AT SINGLE CRYSTAL SURFACES:
CLASSIFICATION, RULES OF FORMATION

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ABSTRACT

The structural information obtained by low energy electron diffraction studies on the chemisorption of gases at single crystal surfaces has been reviewed and tabulated according to the rotational symmetry of the substrate. Analysis of the tables leads to the formulation of three rules: rule of close-packing, rule of rotational symmetry, rule of similar unit cell vectors. From the application of these rules one could predict the structures of other chemisorbed molecules on crystal surfaces.

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INTRODUCTION

LEED has been used to study structures of chemisorbed gases on a large number of single crystal surfaces. In most cases it shows ordered structures depending on the symmetry of the crystal face (substrate), on the chemical and geometrical characteristics of the adsorbed molecule and sometimes on the surface concentration of the adsorbed phase (adsorbate) which is a function of the partial pressure of the gas.

The structures of chemisorbed gases detected by LEED have been gathered into comparative tables and from their comparison, several general rules deduced.

CLASSIFICATION

The classification used is based upon the rotational symmetry of the substrate (6-, 4- or 2- fold). Most data relate to low index faces of centered cubic (c.c.) and face-centered cubic (c.f.c) crystals, fewer to crystals with a diamond or close-packed hexagonal (hex) unit cell.

The most frequently studied gases are oxygen, carbon monoxide, hydrogen, nitrogen, carbon dioxide, which can adsorb as molecular or atomic species. More recently, other types of gases have been used: halogens (Cl_2 , I_2), hydrides (NH_3 , PH_3 , H_2S , H_2Se), hydrocarbons among which olefins with several carbon atoms. Finally, gas mixtures were used ($\text{CO} + \text{O}_2$, $\text{CO} + \text{H}_2$, $\text{CO} + \text{N}_2$, etc.).

In order to designate the structures, one uses a simplified notation containing the following data:

- 1) chemical symbol and crystal face of the substrate,
- 2) unit cell of the adsorption structure (or adsorption unit cell),
- 3) chemical symbol of the adsorbed gas.

The unit cell of the surface structure is defined by the length and orientation of its vectors with respect to those of the substrate unit cell. For example, Ni(100)-(2 × 2) - 0 describes a structure formed by adsorbing oxygen onto the (100) face of nickel; the unit cell vectors of the adsorption structure have the same orientation, but are twice as long as those of the substrate unit cell. For simplicity, the symbol P is omitted in the case of a primitive unit cell. A centered unit cell is designated by the letter C, as for: W(100) - C (2 × 2) - H.

The unit cell vectors of the adsorption structure are not always integer multiples of those of the substrate unit cell, nor are they always parallel to them, as for: Cu(111) - ($\sqrt{3} \times \sqrt{3}$) R-30° - S; this notation indicates that the unit cell vectors of the adsorption structure are multiplied by $\sqrt{3}$ and rotated by 30° with respect to those of the substrate unit cell.

When the exact nature of the adsorbed species is unknown (molecule, atom, radical), the chemical symbol refers to the molecule in the gas phase.

Beside the notations of the ordered structures, the tables also contain the following informations:

- "ads.": structure which has not been given a notation by the authors (complex structure),
- "ord. 1D": one-dimensional order,
- "desord.": disordered phase,
- "non ads.": no adsorption,
- "facet.": faceting,
- "decomp": decomposition

Whenever a three-dimensional compound (for example, an oxide) forms, its formula and epitaxial plane is given.

RULES APPLYING TO THE STRUCTURES OF CHEMISORBED GASES

The experimental data available indicate several tendencies which can be summarized in the form of rules applying to the formation of ordered surface structures. Although empirical and based on the comparison of the structural data available, these rules have a strong physico-chemical foundation. They express that chemisorption yields surface structures characterized by maximum adsorbate-adsorbate and adsorbate-substrate interaction. These rules possess exceptions which are mentioned in due place.

1) Rule of close-packing. Adsorbed atoms or molecules tend to form surface structures having the smallest unit cell allowed by the dimensions of the molecule and the adsorbate-adsorbate and adsorbate-substrate interactions. They preferentially form close-packed arrays.

Structures with large unit cells are rare. Most frequently encountered are those with unit cell vectors equal $[(1 \times 1)]$ or nearly twice larger than those of the substrate unit cell $[(2 \times 2), C(2 \times 2), (\sqrt{3} \times \sqrt{3}), (2 \times 1)]$.

This is particularly true for the adsorption of gas near room temperature: the structure formed (when there is only one) or the first formed (when adsorption of increasing amounts of gas gives rise to a series of structures) has always a small unit cell.

Exceptions can be found in the following cases: substrates having already a large unit cell (Si), structures formed by high temperature

adsorption, by thermal transformation of a phase which is disordered at room temperature, by thermal desorption from another structure, and structures formed by decomposition of a molecule (for example, CO, CO₂, hydrocarbons, with liberation of carbon).

Even large molecules form the smallest possible unit cells [for example, olefins on Pt(111)]. If a sterical hindrance prevents rotation in the surface layer, the adsorbed phase will be disordered rather than ordered in a less dense packing [for example, olefins on Pt(100)].

The tendency towards close-packing indicates that the adsorbate-adsorbate interaction is as strong as the adsorbate-substrate interaction and plays an important role in the formation of surface chemical bonds. The existence of co-adsorbed structures (simultaneous adsorption of two gases) is supplementary evidence. (26, 72, 72, 82, 91, 93, 108) The strong interaction between the two types of molecules in the adsorbed layer gives rise to a composite unit cell, often different from the unit cell formed by each of the components alone.

2) Rule of rotational symmetry. Adsorbed atoms or molecules form ordered structures, which possess the same rotational symmetry as the substrate.

The substrates can be classified into three groups according to their rotational symmetry:

- 6-fold symmetry: *c.f.c. (111), c.c. (111), diamond (111), hexagonal (0001),
- 4-fold symmetry: c.f.c. (100), c.c. (100),
- 2-fold symmetry: c.f.c. (110), c.c. (110), c.c. (211).

* Considering only the first atomic layer of the surface; the symmetry reduces to 3 if one considers two adjacent layers.

In the case of 6-fold symmetry, the structures are most frequently of the type: (2×2) , $(\sqrt{3} \times \sqrt{3})R-30^\circ$. For a 4-fold symmetry, the most usual structures are: $C(2 \times 2)$, (2×2) . For a 2-fold symmetry, one finds mainly: $C(2 \times 2)$ and structures of the type: $(m \times n)$ or $C(m \times n)$ with m different from n .

In some cases, the adsorption unit cell has a lower symmetry than the substrate: one observes then the existence of domains. For example, considering a (2×1) unit cell on a (100) face, one finds two domains rotated by 90° ; for a $C(2 \times 4)$ unit cell on a (111) face, one finds 3 domains rotated by 120° . These domains allow to reach a higher degree of coverage, hence closer packing (rule 1) than a unit cell having the same symmetry as the substrate.

3) Rule of similar unit cell vectors. Atoms or molecules adsorbed in monolayers tend to form ordered surface structures, the unit cell of which is closely related to that of the substrate.

Practically, all the unit cells of chemisorbed gases can be defined with respect to a basis formed by the unit cell vectors of the substrate. Their unit cell vectors are integer multiples of those of the substrate unit cell [for example (2×2)] or of the substrate unit cell rotated by a given angle [for example, $[(\sqrt{3} \times \sqrt{3}) R-30^\circ, (3\sqrt{2} \times \sqrt{2}) R-45^\circ]$. Thus adsorbed particles tend to accommodate to the pre-existing surface structure and obey the substrate periodicity.

This rule is no longer valid when reconstruction of the surface leads to a true bidimensional compound (for example, a sulfide or carbide) (35, 36, 41) the unit cell of which is no longer determined by the substrate. The considerable mismatch between the surface layer and the substrate shows by a coincidence unit cell with large periodicity,

rotated by a given angle with respect to the substrate unit cell; a fraction only of the atoms of the surface layer coincide with substrate atoms.

This rule also loses its validity when the reaction goes beyond a chemisorbed layer and favors the epitaxial growth of a 3 dimensional compound (for example, NiO on the various faces of nickel) ⁽⁶⁾. However, if the mismatch is small, the surface unit cell may tend to adapt to the substrate unit cell. LEED patterns enable to monitor such a transformation (appearance of streaks, doubling of spots). A deformed transition layer has been found during the growth of a FeO(111) film over the (110) face of iron: ⁽⁸⁷⁾ there is a superposition of a substrate Fe layer, an adapted FeO layer and a normal FeO layer.

CONCLUSION

The meaning of the three rules can be summarized as follows. The rule of close-packing shows the importance of adsorbate-adsorbate interactions. The rules of rotational symmetry and similar unit cell vectors result from the adsorbate-substrate interactions.

It appears also from a study of the tables that, according to the symmetry of the substrate, certain structures occur far more frequently than others. By a suitable application of these rules, one can hope to predict new surface structures which have not been studied until now or which are difficult to study because of the high vapor pressure of the single crystal or its difficult preparation.

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Table I. Adsorption unit cells on substrates with 6-fold symmetry

Gaz adsorbé	c.f.c. Ag (111)	c.f.c. Cu (111)	c.f.c. Ni (111)	c.f.c. Pt (111)	c.f.c. Rh (111)	c.f.c. UO ₂ (111)	c.f.c. Mo (111)
O ₂	⁽¹⁾ (2 × 2) — 0 ⁽¹⁾ (√3 × √3)R30° — 0	⁽⁷⁾ désord. ^(7, 8) (7 × 7) — 0 ^(7, 8) (√3 × √3) R30° — 0 ^(7, 8) (2 × 2) — 0 ⁽⁸⁾ (3 × 3) — 0 ⁽⁹⁾ (11 × 5)R5° — 0 ⁽²⁶⁾ non ads.	^(2, 3, 4) (2 × 2) — 0 ^(2, 5) (√3 × √3)R30° — 0 ^(4, 6) NiO (111)	^(10, 11) (2 × 2) — 0	⁽¹²⁾ (2 × 2) — 0	⁽¹³⁾ (3 × 3) — 0 ⁽¹³⁾ (2√3 × 2√3) R30° — 0	⁽¹⁴⁾ facet. (211)
CO			⁽⁵⁾ (2 × 2) — CO ⁽⁵⁾ (√3 × √3)R30° — 0 ⁽⁵⁾ (√7 × √7)R19° — CO ⁽⁵⁾ (2 × √3) — CO ₂ ^(5, 27) (√39 × √39) × C ⁽⁵⁾ (2 × 2) — CO ₂ ⁽⁵⁾ (√3 × √3)R30° — U ⁽⁵⁾ (2 × √3) — CO ₂ ^(5, 27) (√39 × √39) — C	⁽²⁸⁾ C(4 × 2) — CO	⁽¹²⁾ (2 × 2) — CO		
CO ₂			⁽⁵⁾ (2 × 2) — CO ₂ ⁽⁵⁾ (√3 × √3)R30° — U ⁽⁵⁾ (2 × √3) — CO ₂ ^(5, 27) (√39 × √39) — C				
H ₂		⁽⁷⁾ non ads.	⁽⁴⁾ (1 × 1) — H ⁽²⁸⁾ (2 × 2) — H ⁽²¹⁾ non ads.				
N ₂							
NH ₃							
PH ₃							
P							
H ₂ S		⁽²⁸⁾ (√3 × √3)R30° — S ⁽²⁸⁾ ads.	⁽²⁸⁾ (2 × 2) — S ⁽²⁸⁾ (√3 × √3)R30° — S ⁽²⁸⁾ (5 × 5) — S ⁽²⁸⁾ ads.				
H ₂ Se							
Cl ₂							
I ₂							
H ₂ + O ₂				⁽¹¹⁾ (√3 × √3)R30°			
CO + O ₂	⁽²⁷⁾ (2 × √3) — (CO + O ₂)						
CH ₄							
C ₂ H ₄		⁽²⁸⁾ non ads.	^(29, 30) (2 × 2) — C ₂ H ₄ ⁽²⁹⁾ ads.	⁽²⁸⁾ (2 × 1) — C ₂ H ₄ ⁽⁴⁰⁾ (2 × 2) — C ₂ H ₄ ⁽²⁸⁾ (2 × 1) — C ₂ H ₂ ⁽²⁸⁾ (2 × 1) — C ₃ H ₆			
C ₂ H ₂			⁽²⁹⁾ (2 × 1) — C ₃ H ₆ ⁽²⁹⁾ (√7 × √7)R19° — C				
C ₃ H ₆			⁽²⁹⁾ (2 × 2) — C ₂ H ₆ ⁽²⁹⁾ (√7 × √7)R19° — C				
C ₂ H ₆				⁽²⁸⁾ (2 × 2) — C ₄ H ₆ ⁽⁴⁰⁾ (2 × 2) — C ₄ H ₆ ⁽²⁸⁾ (√7 × √3)R13,9°			
2-butène							
butadiène							
iso-butylène							

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Table I. continued

c.f.c. W (111)	diamant diamant (111)	diamant Ge (111)	diamant Si (111)	hex Be (0001)	hex Re (0001)	hex Ru (0001)	hex Ti (0001)	hex Cds (0001)
⁽¹⁵⁾ facet. (211)	⁽¹⁶⁾ ads.	^(17, 18) désord. ⁽¹⁹⁾ (1 × 1)	^(17, 20, 21) désord.	⁽²²⁾ désord.	^(23, 24) (2 × 2) — O	⁽¹²⁾ (2 × 2) — O	⁽¹⁸⁾ (1 × 1) — O	⁽²⁵⁾ désord.
				⁽²²⁾ désord.	⁽²⁴⁾ non ads. ⁽²³⁾ (2 × 2) — CO	⁽¹²⁾ ($\sqrt{3} \times \sqrt{3}$) — CO R30° — CO ⁽¹³⁾ (2 × 2) — CO	⁽¹⁸⁾ (1 × 1) — CO	
						⁽¹³⁾ ($\sqrt{3} \times \sqrt{3}$) — CO ₂ R30° — CO ₂ ⁽¹³⁾ (2 × 2) — CO ₂		
	⁽³⁰⁾ (1 × 1) — H			⁽²²⁾ non ads.	⁽²⁴⁾ non ads.			
				⁽²²⁾ non ads.	⁽²⁴⁾ non ads.			
	⁽³⁰⁾ ($\sqrt{3} \times \sqrt{3}$) R30° — P	⁽¹⁹⁾ (1 × 1) — P	⁽²⁴⁾ (8 × 8) — N ^(23, 25) (6 $\sqrt{3} \times 6\sqrt{3}$) — P ⁽²³⁾ (1 × 1) — P ⁽²³⁾ (2 $\sqrt{3} \times 2\sqrt{3}$) — P ⁽²⁵⁾ (4 × 4) — P					
		⁽³⁷⁾ (2 × 2) — S						
		⁽³⁷⁾ (2 × 2) — Se						
			⁽²⁸⁾ désord. ⁽²⁸⁾ (7 × 7) — Cl ⁽²⁸⁾ (1 × 1) — Cl ⁽²³⁾ (1 × 1) — I					
⁽⁴¹⁾ (6 × 6) — C								

Table II. Adsorption unit cells on substrates with 4-fold symmetry.

Gaz adsorbé	c.f.c. Al (100)	c.f.c. Cu (100)	c.f.c. Ir (100)	c.f.c. Ni (100)	c.f.c. Pd (100)	c.f.c. Pt (100)	c.f.c. Rh (100)
O ₂	(42, 43, 44) désord.	(9, 45) (1 × 1) — O (9, 45, 46) (2 × 1) — O (46) (2 × 2) — O (7, 47) (2 × 4) R45° — O (7, 47) ads.	(48) (2 × 1) — O (48) (5 × 1) — O	(2, 49, 50, 51) (2 × 2) — O (2, 52, 53, 54, 55, 56, 57, 5) (2 × 2) — O (6) NiO (100)			C(2 × 8) — O
CO		(28) (2 × 2) — C	(48) C(2 × 2) — CO	(54, 55, 58) (2 × 2) — CO (69) (2 × 2) — CO	(70) désord. (70) C(4 × 2) — CO (71) (2 × 4) R45° — CO	(28, 72, 73) C(4 × 2) — CO (28, 72, 73) (3√2 × √2) R45° — CO (72, 73) (√2 × √5) R45° — CO (10) (2 × 4) — CO (10) (1 × 3) — CO	(58) (4 × 1) — CO
CO ₂			(48) C(2 × 2) — CO ₂ (48) (7 × 20) — CO ₂	(79) décomp. (2 × 2) — O (79) C(2 × 2) — CO			
H ₂						(72, 74) (2 × 2) — H	
N ₂		(49) (1 × 1) — N (47) C(2 × 2) — N		(80, 81) non ads.			
NH ₃							
H ₂ S		(30) (2 × 2) — S (35) ads.		(88) (2 × 2) — S (88) C(2 × 2) — S			
SO ₂				(88) C(2 × 2) — SO ₂ (88) (2 × 2) — SO ₂			
I ₂ CO + H ₂						(72, 74) C(2 × 2) — (CO + H ₂)	
CO + N ₂							
CH ₄ C ₂ H ₄		(28) (2 × 2) — C ₂ H ₄		(88) C(2 × 2) — C ₂ H ₄ (88) (√7 × √7) R19° — C		(28, 72) C(2 × 2) — C ₂ H ₄	
C ₂ H ₂						(28, 72) C(2 × 2) — C ₂ H ₂ (28) désord. (28) désord. (28) désord. (28) désord.	
C ₃ H ₆							
2-butène							
iso-butylène							
butadiène							

Table II. continued

c.c. Cr (100)	c.c. Fe (100)	c.c. Mo (100)	c.c. V (100)	c.c. W (100)	diamant diamant (100)	diamant Ge (100)	diamant Si (100)
$(2 \times 2)^{(59)} - O$	$C(2 \times 2)^{(60)} - O$ $FeO(100)$	$(61, 62, 63, 64)$ désord. $C(2 \times 2)^{(61, 62)} - O$ $(1 \times 1)^{(61)} - O$ $(\sqrt{5} \times \sqrt{5})$ $R26^\circ - O$ $(2 \times 2)^{(61)} - O$ $C(4 \times 4)^{(64)} - O$ désord. $(63, 64)$ $(1 \times 1)^{(64)} - CO$ $C(2 \times 2)^{(64)} - CO$ $(4 \times 1)^{(64)} - CO$	$(1 \times 1)^{(65)} - O$ $(2 \times 2)^{(65)} - O$	$(4 \times 1)^{(66)} - O$ $(2 \times 1)^{(66, 67)} - O$ $(2 \times 2)^{(68)} - O$ facet. (110)	(16) désord. (16) ads.	$(17, 18)$ désord. $(17, 18)$ $(1 \times 1) - O$	$(17, 18, 20)$ $(1 \times 1) - O$ $(17, 18, 20)$ facet (111)
$(2 \times 2)^{(59)} - CO$				(75) désord. $(66, 75)$ $C(2 \times 2) - CO$			
$(2 \times 2)^{(69)} - N$		(77) $C(4 \times 2) - H$ (77) $(1 \times 1) - H$ (82) $(1 \times 1) - N$	(84) désord.	$(69, 78, 79)$ $C(2 \times 2) - H$ (79) $(2 \times 5) - H$ (79) $(4 \times 1) - H$ $(66, 82)$ $C(2 \times 2) - N$ (84) désord. (84) $C(2 \times 2) - NH_3$ (84) $(1 \times 1) - HN_3$			
	(85) $C(2 \times 2) - S$ (85) $C(22 \times 2)R45^\circ - S$ (85) $C(18 \times 2)R45^\circ - S$ (85) $C(14 \times 2)R45^\circ - S$ (85) $C(10 \times 2)R45^\circ - S$			(83) (4×1) $-(CO + N_2)$ (81) $(5 \times 1) - C$		(19) $(3 \times 3) - I$	(83) $(3 \times 3) - I$

Table III. Adsorption unit cells on substrates with 2-fold symmetry.

Gaz adsorbé	c.f.c. Cu (110)	c.f.c. Ni (110)	c.f.c. Pd (110)	c.f.c. Pt (110)	c.f.c. Rh (110)	c.c. Fe (110)	c.c. Mo (110)
O ₂	(7, 8, 9, 45, 46) (2 × 1) — O (8, 9, 45, 46) C(6 × 2) — O (8) (5 × 3) — O	(2, 3, 51, 57, 89, 90, 91, 92, 93) (2 × 1) — O (2, 51, 89, 91, 92, 93, 94) (3 × 1) — O (2, 89) (5 × 2) — O (8, 89) (5 × 1) — O (51) (9 × 4) — O (8, 51, 91, 93) NiO (100)	(85) (1 × 3) — O (85) (1 × 2) — O (85) C(2 × 4) — O (85) C(2 × 6) — O (85) ads.	(11) (2 × 1) — O (11) (4 × 2) — O	(86, 87) désord. (86, 87) C(2 × 4) — O (87, 88) C(2 × 6) — O (86, 87) C(2 × 8) — O (86, 87) (2 × 2) — O (86, 87) (2 × 3) — O (86, 87) C(2 × 2) — O (86, 87) (1 × 2) — O (86, 87) (1 × 3) — O	(87, 88, 89) C(2 × 2) — O (87, 88, 89) C(3 × 1) — O (88) C(1 × 5) — O (88) (2 × 8) — O (87, 88, 89) FeO (111)	(82, 83, 100) (2 × 2) — O (82, 83, 100) (2 × 1) — O (82, 83) (1 × 1) — O
CO	(86) ord. 1D (86) (2 × 3) — C	(8, 94) (1 × 1) — CO	(85) (5 × 2) — CO (85) (2 × 1) — CO				(82, 100) (1 × 1) — CO (84) C(2 × 2) — CO
CO ₂							(84) désord. (100) ads. (84) (1 × 1) — N
H ₂	(7) non ads.	(89, 91, 94, 110) (1 × 2) — H					
N ₂							
H ₂ O	(86) désord.	(110) (2 × 1) — H ₂ O					
NH ₃							
SH ₂	(83) C(2 × 2) — S (86) ads.	(36) C(2 × 2) — S (86) (3 × 2) — S (81) (3 × 1) — (C(1) + N ₂)				(114) (2 × 4) — S (114) (1 × 2) — S	
CO + O ₂							
CH ₄							
C ₂ H ₄	(86) Ord. 1D						

Table III continued

c.c. Nb (110)	c.c. Ta (110)	c.c. V (110)	c.c. W (110)	c.c. Mo (211)	c.c. Ta (211)	c.c. W (211)	diamant Ge (110)
$(3 \times 1) \xrightarrow{(101)} \text{O}$ oxyde	$(3 \times 1) \xrightarrow{(101, 102)} \text{O}$ oxyde	$(3 \times 1) \xrightarrow{(101)} \text{O}$	$(2 \times 1) \xrightarrow{(57, 102)} \text{O}$ (104) $C(2 \times 2) \xrightarrow{(104)} \text{O}$ $(2 \times 2) \xrightarrow{(104)} \text{O}$ $(1 \times 1) \xrightarrow{(104)} \text{O}$ $(57, 102, 104)$ $C(14 \times 7) \xrightarrow{(104)} \text{O}$ $C(21 \times 7) \xrightarrow{(104)} \text{O}$ $C(48 \times 18) \xrightarrow{(104)} \text{O}$	$(2 \times 1) \xrightarrow{(105)} \text{O}$ $(1 \times 2) \xrightarrow{(105)} \text{O}$ $(1 \times 3) \xrightarrow{(105)} \text{O}$ $C(4 \times 2) \xrightarrow{(105)} \text{O}$	$(3 \times 1) \xrightarrow{(101, 102)} \text{O}$ oxyde	$(15, 105, 107, 108)$ $(2 \times 1) \xrightarrow{(15, 108)} \text{O}$ $(1 \times 2) \xrightarrow{(108)} \text{O}$ $(1 \times n) \xrightarrow{(108)} \text{O}$ $n = 1, 2, 3, 4$ $(1 \times 1) \xrightarrow{(107)} \text{O}$	$(17, 18)$ désord. $(17, 18)$ (1×1)
(101) désord. (101) décomp. $\rightarrow$ $(3 \times 1) \xrightarrow{(101)} \text{O}$	$(101, 102)$ désord. $(101, 102)$ décomp. $\rightarrow$ $(3 \times 1) \xrightarrow{(101)} \text{O}$	(101) désord. (101) décomp. $\rightarrow$ $(3 \times 1) \xrightarrow{(101)} \text{O}$	(109) désord. (109) $C(9 \times 5) \xrightarrow{(109)} \text{CO}$	(105) désord. (105) ads.	$(101, 103)$ désord. (103) décomp. $\rightarrow$ $(3 \times 1) \xrightarrow{(103)} \text{O}$	(108) désord. (108) $C(6 \times 4) \xrightarrow{(108)} \text{CO}$ $(2 \times 1) \xrightarrow{(108)} \text{CO}$ $C(2 \times 4) \xrightarrow{(108)} \text{CO}$ (108) ads.	
$(1 \times 1) \xrightarrow{(111)} \text{H}$	$(1 \times 1) \xrightarrow{(102)} \text{H}$ (101) non ads.			$(1 \times 2) \xrightarrow{(105)} \text{H}$ (105) non ads.	$(1 \times 1) \xrightarrow{(103)} \text{H}$ (103) désord. (103) facét. (311)	$(1 \times 1) \xrightarrow{(112)} \text{H}$ $C(4 \times 2) \xrightarrow{(113)} \text{NH}_3$	
			(92) $C(11 \times 5) \xrightarrow{(92)} \text{CO} + \text{O}_2$ (41) $(15 \times 3) \text{R}\alpha \xrightarrow{(41)} \text{C}$ $(15 \times 12) \text{R}\alpha \xrightarrow{(41)} \text{C}$			$(1 \times 1) \xrightarrow{(108)} \text{CO} + \text{O}_2$ $(1 \times 2) \xrightarrow{(108)} \text{CO} + \text{O}_2$	