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An arrangement of the chemical elements in several classes inside the periodic table according to their common properties

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Abstract

Whereas they are very diverse, it is of a scientific and practical interest to collect the chemical elements in several classes according to their common properties inside the periodic table. Metals and inert gases form two well-definite classes. The 20 other elements, ranged beyond the ‘non-metals’ are present in the quasi totality of the chemical compounds, and thus deserve to be named ‘panelements’. Very diverse, the panelements may be divided in two classes and situated with respect to the metals by their names: ‘metalloids’ and ‘antimetals’. Only the primordial hydrogen remains solitary. All these data may be easily introduced in the periodic table. *To cite this article:* A. Hérold, C. R. Chimie 9 (2006).

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Résumé

Un regroupement des éléments chimiques en plusieurs classes, à l’intérieur du tableau périodique, selon leurs propriétés communes. Les éléments chimiques étant très divers, il est scientifiquement et pratiquement utile de les réunir en plusieurs classes, selon des propriétés communes, dans le cadre de la classification périodique. Métaux et gaz nobles forment deux classes bien définies. Les vingt autres éléments qui font partie des « non-métaux » sont présents dans la quasi-totalité des composés chimiques et méritent donc d’être nommés « panéléments ». Très divers, ils peuvent être divisés en deux classes, et situés vis-à-vis des métaux par leurs noms : « métalloïdes » et « antimétaux ». Seul le primordial hydrogène demeure solitaire. Toutes ces données peuvent être aisément jointes au tableau périodique. *Pour citer cet article :* A. Hérold, C. R. Chimie 9 (2006).

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1. Introduction

Classification and nomenclature are the bases of any knowledge. In the periodic table of the elements [1] – a remarkable example of classification – each column

contains a series of elements which have the same number of valence electrons. Nevertheless it is clear that, in the column 1, hydrogen is quite different from the alkali metals. Similarly, each of the columns 13–16 contains several elements which strongly differ from one another. Therefore, it seems that an arrangement of the elements in several classes, according to their main common properties is of a scientific and practical interest and deserves to be studied and carried out.

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2. The metals and the metallic state

The metals form more than the three quarters of the elements. Their physical and chemical properties strongly vary according to the number of their valence electrons. But they have several common properties that define the metallic state and characterize a class [2].

2.1. The metals crystallize in three-dimensional (3D) compact lattices. The number of strong bonds between one atom and their neighbors (number of coordination NC) is 12 in the cubic face centered and hexagonal compact lattices. In the cubic centered lattice each atom exchanges with its neighbors eight short bonds and six bonds longer of about 15%. Most metals crystallize in these three systems. Many crystallize in two structures, according to the temperature. The physical properties of these metallic structures are the same in any directions: they are isotropic. Moreover they contain a single type of strong bond, the metallic one: they are homodesmic, according to the classification of Evans [3].

The structures of zinc and cadmium are close to the hexagonal compact one, but the distance between the hexagonal atomic planes is 190 nm instead of 163 in the perfect structure. Therefore these elements are not quite isotropic and homodesmic. Similarly the quadratic stable variety of tin is partly anisotropic and heterodesmic. Nevertheless these elements, which possess the other characters of the metallic state belong to the metals.

2.2. The number of coordination in the metals is always higher than the number of valence electrons, so that the lattice cohesion arises from a resonance phenomenon between the different bonds. Consequently, the metallic bond is no directional, and the valence electrons are delocalized.

These characters allow the sliding of the atomic planes with respect to their neighbors – by the intermediate of dislocations – without breaking the crystal-line lattice. Therefore, the metals are able to accept a “plastic deformation”, they are malleable and ductile.

On the other hand, the delocalization of the valence electrons gives to the metals a high electrical conductivity. It decreases by increasing temperature, on account of the thermal oscillations of the atoms, which hinder the electron motion.

2.3. The most general chemical property of the metals is their capacity for giving up electrons and becoming cations. The best electron donors are the alkali and the alkaline earth metals from which the electronegativity X in the Pauling's scale is close to 1. That capacity decreases by increasing the number of valence electrons, and becomes very small for the metals of the

second and third triads of the periodic table ($X = 2.2$) and much more for gold from which the electronegativity equals that of selenium (2.4). Nevertheless these elements which are more electronegative than hydrogen ($X = 2.1$) are not excluded for the metal class.

The metallic character of an element more depends on its structure and its physical properties than on its chemical ones. This remark will be also valid in other element classes.

3. The inert gases

These non-metallic elements which occupy the column 18 of the periodic table form a second definite class, although they differ from one another in their densities and their boiling points which increase with the atomic number. Indeed, they are the least active of the elements, even if the three heaviest are able to react with fluorine and other very oxidizing reagents. Therefore they are monoatomic and crystallize at low temperature in highly symmetrical lattices by the effect of no directional Van der Waals attractions ($NC = 0$).

4. A large series of ‘non-metals’: the panelements

The elements others than the metals and the inert gases are hydrogen and a series of 18 elements of the columns 13–17 (the unstable astatine excluded). For a long time they were named ‘metalloids’. But this term, which suggests some analogies with the metals, is not valid for elements such as oxygen, nitrogen, and halogens.

Therefore, these 19 elements are ranged without any order in the lumber-room of the ‘non-metals’. This expression is not inexact but does not say anything about their activity which is of a fundamental importance in the whole chemistry: indeed all the chemical compounds – except the intermetallic ones – contain one, several or many of these elements. Of course, they are present in all the minerals from which the metals are extracted. Therefore, these ‘non-metals’ deserve to be named ‘panelements’ (from the Greek τὸ πᾶν, the whole).

In the solid state, the panelements form lattices much less compact than the metals. Silicon and germanium have the cubic type diamond homodesmic structure ($NC = 4$). All the other panelements contain both covalent and Van der Waals bonds, thus they are heterodesmic with NC between 3 and 1.

5. Metalloids and antimetals [4]

The name ‘panelements’ corresponds to their activity in the whole chemistry. Moreover they are very diverse and – except hydrogen – they may be divided in two well-characterized classes:

- the elements highly electronegative ($X \geq 2.5$ in the Pauling’s scale) will be named ‘antimetals’: indeed, whereas the metals are electron donors, the antimetals are electron acceptors; they attack the metals by capture of their valence electrons and become anions whereas the metals become cations;
- for the elements of middle electronegativity ($2 < X \leq 2.5$), the ancient term ‘metalloid’ is valid: it situates the corresponding elements, which have some analogies with the metals between these latter and the antimetals.

Both classes differ from one to another not only in their electronegativity, which affects their chemical properties, but also in their crystalline lattices: the antimetals form molecular rather similar lattices, whereas the metalloid lattices are macromolecular and very diverse.

6. Commentary on tables

The data contained in tables which are classical have been mainly derived from the Refs. [5–7]. Scheme 1 situates the seven antimetals and the metalloids in the periodic table.

Tables 1 and 2 summarize some physical and chemical properties of the antimetals (on the right) and the metalloids (on the left).

- Tables 1 and 2 show that in each class the elements have a series of common properties which differ from one class to the other. Therefore the division of the panelements in antimetals and metalloids is valid, even if several elements have not all the properties of their class.
- Remarks relative to several elements:
 - graphite. The carbon electronegativity ($X = 2.5$) equals those of sulfur and iodide, so that several ionic carbides (acetylides) such as Li_2C_2 and $(\text{Ca}, \text{Ba}, \text{Sr}) \text{C}_2$ may be obtained by direct synthesis. But graphite, the stable variety of carbon, crystallizes in a lamellar structure which is refractory and conductive of electricity: thus it is evidently a metalloid;
 - nitrogen. In account of its volatility, its electronegativity equal to that of chlorine ($X = 3$) and the existence of ionic nitrides (Li_3N , $\text{Ca}_3\text{N}_2\dots$) obtained by direct synthesis, nitrogen is an antimetal. Its weak chemical reactivity, much less than that of chlorine, is a consequence of the strong stability of the N_2 molecule due to its triple bond;
 - phosphorus is generally known in its white molecular form (P_4) which is volatile and very reactive and, therefore may be compared to an antimetal. Nevertheless, it has to be ranged in the metalloids: indeed its electronegativity ($X = 2.1$) is too small for an antimetal. Moreover, its stable black variety is rhombohedral and conductive of electricity as the following elements of the column 15;
 - Selenium and sulfur have almost the same electronegativity ($X = 2.4$ for Se, 2.5 for S) and their chemical activities are comparable. But the stable structure of sulfur is molecular (S_8) and insulating,

Columns of the periodic table					
13	14	15	16	17	18
Panelements (except H)					Inert gases
Metalloids			Antimetals		He
B	C	N	O	F	Ne
Al	Si	P	S	Cl	A
Ga	Ge	As	Se	Br	Kr
In	Sn	Sb	Te	I	Xe
Tl	Pb	Bi	Po	At ?	Rn
Metals					

Scheme 1. Situation of the metalloids and antimetals in the periodic table.

Table 1
Comparison between metalloids and antimetals: structures and physical properties

Metalloids	Antimetals
<ul style="list-style-type: none"> ● Many allotropies between the molecular and the stable structures for P, As, Sb, Se, Te ● Stable covalent or macromolecular structures ○ Homodesmic 3D: Si, Ge, cubic diamond type (NC = 4) ○ Heterodesmic 2D: C hexagonal with plane sheets and B, P, As, Sb, Bi rhombohedral with folded sheets (NC = 3) ○ Heterodesmic 1D: Se, Te hexagonal with helicoïdal fibers (NC = 2) High reticular energies <ul style="list-style-type: none"> ● Crystalline lattices hard and brittle ● Densities lower than those of the neighbor metals but higher than those of the neighbor antimetals ● Melting points strongly higher than those of the neighbor antimetals and metals ● No or very small (Te) solubility in the homopolar solvents Electrical conductivities small or very small, (much lower than those of the neighbor metals) increasing with temperature by electron transfer in the conduction band	Molecular structures <ul style="list-style-type: none"> ● Diatomic molecules, except S₈ ● NC = 1 except N₂ (3), O₂ and S₈ (2) ● In solid state, Van der Waals no directional bonds between the molecules, leading to compact heterodesmic lattices Lattices of small reticular energy <ul style="list-style-type: none"> ● Solids of small hardness ● Densities higher than those of the neighbor inert gases, but much lower than those of the neighbor metalloids ● Low melting points and boiling points: only iodine and sulfur are solid at room temperature ● Solubility in the homopolar solvents small for N₂ and O₂, but high for the other elements Electrical insulators

Table 2
Comparison between metalloids and antimetals: chemical properties

Metalloids	Antimetals
Moderate to weak reactivity, which often requires high temperatures Compounds with metals <ul style="list-style-type: none"> ● Ionic carbides (acetylides) of Li, Ca, Sr, Ba, obtained by direct synthesis ● Many ionocovalent, homopolar and interstitial compounds, refractory for the carbides and borides, generally fusible above 700 °C for the others ● Alloys: carbon and silicium steels – alloys with fusible metals for Sb and Bi Compounds with hydrogen <ul style="list-style-type: none"> ● Direct synthesis possible at high temperature but not used ● Indirect synthesis for all the metalloids ● Acid functions only for H₂Se (weak) and for H₂Te (middle) ● Compounds in chains and cycles for B, C, Si (H/M > 2) Higher oxides leading to weak Brönsted acids, except H ₃ PO ₄ (middle) and H ₂ SeO ₄ (strong)	High reactivity increasing with electronegativity Compounds with the metals <ol style="list-style-type: none"> 1. Direct exothermic reactions often very brisk leading to a very high number of ionic and ionocovalent compounds diverse in their properties 2. Melting points and boiling points decreasing along the series O–N–S–F–Cl–Br–I Besides many refractory oxides, the halides of a high oxidation state are easily volatile and sometimes liquid. Compounds with hydrogen <ol style="list-style-type: none"> 1. Direct exothermic synthesis (A + H₂) always possible (but not always used) leading to gaseous or liquid (HF, H₂O) molecules 2. Acid functions for 5 of the 7 antimetal compounds: weak for H₂S, middle for HF, strong for HCl, HBr and HI 3. Hydrogen polysulfides in chains synthesized by indirect way (H/S ratio < 2) Higher oxides of N, S, Cl, Br, I leading to strong Brönsted acids

whereas the stable selenium form (silver-gray or ‘metallic’ selenium) is macromolecular hexagonal as tellurium. Its electrical conductivity, very small in the dark rapidly increases with the light intensity. Therefore sulfur has to be ranged in the antimetals, and selenium in the metalloids.

- In brief the important differences between the metalloids and the antimetals mainly depend on their structures: covalent or macromolecular for the former, molecular for the latter. Consequently the proposed division of the panelements in metalloids and antimetals becomes evident.

7. Use of the antimetals and metalloids

All the panelements are chemically active. In account of their low melting and boiling points, due to their molecular structure, the antimetals are only used as chemical reagents. On the contrary their macromolecular structure allows to use the metalloids as materials. For instance graphite is used for its mechanical and thermal properties and also as a conductor of electricity, silicium and selenium for their electronic properties. These data confirm the difference between these two element classes.

8. Relations between metals and metalloids

From the top to the bottom of the columns 13–16 of the periodic table the electronegativity of the elements decreases and their metallic character increases. So, in the column 13, aluminum, the second element is a metal. In the column 14, it is only tin, the fourth element (in its white stable form) which is a metal. What about the columns 15 and 16? Antimony and bismuth are sometimes considered as metals for their ability to form alloys with the former. But they do not possess any of the main properties of the metallic state (see Section 2) and therefore have to be ranged beyond the metalloids. Owing to the evolution from the column 13 to the column 15, polonium is certainly a metalloid too.

9. Hydrogen

On account of the chemical activity of the molecule H_2 , hydrogen is evidently a panelement. But owing to its physical properties it is not a metalloid. Moreover on account of its low electronegativity ($X=2.1$) and its ability to become a cation, it cannot take place beyond the antimetals. This primordial element and the most present in the universe is well situated alone at the beginning of the periodic table.

10. An arrangement of the elements according to their electrical conductivity

The electrical conductivity measurements naturally leads to divide the elements in three classes: the metals, the ‘semi-metals’ and the ‘non-metals’. What are the relations of these classes with those clearly defined previously?

- Actually the semi-metals of the physicists correspond almost exactly to the metalloids and thus confirm that these elements form a class. Nevertheless the metalloids are very diverse: for instance bismuth is closer to the metallic state than arsenic. Thus the term metalloid seems to be preferable to the expression semi-metal which suggests that the relation metal–semi-metal is quantitative (semi = 1/2), and is the same for all the semi-metals.
- The elements other than the metals and semi-metals are isolating, and therefore may be ranged in the non-metals. But this ‘class’, valid for the electrical conductivity studies cannot be generalized: indeed, neglecting the chemistry, it mixes the antimetals and the inert gases: thus the most active and the least active elements of the whole chemistry.

11. Others arrangements of the elements in several periodic tables

During the last 15 years, a series of inorganic and physical chemistry books have been published which contain various element arrangements inside the periodic table.

- The periodic table contained in [8] situates hydrogen in the line 1, over and between the columns 7 and 8 in agreement with its middle electronegativity (2.1) and its ability to become both anion or cation. Helium is placed on the top of the column 18. The other elements are divided in metals and non-metals. These latter are situated on the right and over the broken line Al, Ge, Sb Po. Therefore Ge, Sb, Bi and Po are included in the metals: a debatable arrangement!
- The periodic table contained in [9,10] differ in the situation of hydrogen and helium. In [9] hydrogen is situated in line 1 over and between the columns 8 and 9, for the same reasons as in [8], and helium is on the top of column 18, in agreement with its atomic number and its physical and chemical properties.

In [10] hydrogen is situated on the top of the column 1 and helium in the top of column 2, both in agreement with their electronic structures. The distribution of the other elements, the same in the both periodic tables is the following:

- block s: columns 1 and 2: typical elements;
- block d: columns 3–12: transition elements;
- block p: columns 13–18: post-transition elements.

(The block f concerns the lanthanides and actinides which do not interest the present article).

It is clear that this arrangement of the elements, founded on the electron distribution round the nucleus, is valid and is of a scientific and pedagogic interest. It is clear too, that it is quite different from the arrangement proposed in the present article which is founded on the element structures and also on their physical and chemical properties.

12. Summary and conclusion

The present text shows that, although they are very diverse, the chemical elements possess in their structures and physical properties and also in their chemical ones a series of common characters, so that they may be ranged in four definite classes: the metals, the inert

gases, the metalloids and the antimetals. This classification is founded on a series of well known experimental data relative to the elements *in their stable allotropic forms*. Only hydrogen does not belong to any of the four classes. This primordial element and the most present in the universe is well situated alone at the beginning of the periodic table.

The neologism “antimetal” designates the elements of which the chemical activity is opposite to that of the metals, and which attack the metals by capture of their valence electrons.

Metalloid is an ancient term, at present unusual, but which is quite valid for a series of elements which have some analogies with the metals. It seems to be preferable to the synonymous expression semi-metal often used by the physicists, which appears too quantitative (semi = 1/2) and uniform for a series of very diverse elements.

Finally this text proposes a rational solution of an old unsolved problem: the arrangement of the elements in several classes. It set in order the elements other than the metals and the inert gases. According to their pre-

sence in the whole chemistry they deserve to be named ‘panelements’.

Of course as shown in [Scheme 1](#) the domains and the names of the different classes may be easily introduced in the periodic table, which therefore gives about those a general view.

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