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Configuration and Properties of Group III Elements in the Periodic Table

Ukpaka Chukwuemeka Peter[1], Joy Chukwuemeka Peter Ukpaka[2], Victor Chukwuemeka Ukpaka[3,*], Abraham Peter Ukpaka[4]

Abstract

Group III elements comprise those found in the third column of the periodic table, including boron, aluminum, gallium, indium, and thallium. These elements possess three valence electrons in their outermost shell, characterized by the electron configuration ns^2np^1, which influences their location and characteristics within the periodic table. The distribution of electron pairs, formal charges, oxidation states, and molecular morphologies of Group III elements and their compounds are illustrated in this study using Lewis structures. Lewis structures provide a visual depiction of a molecule's valence electrons and bonds. For five representative compounds associated with each element—specifically trihalides, oxides, hydroxides, boranes, and aluminosilicates—Lewis structures were constructed following established rules and conventions. Using the concepts of Lewis structures and VSEPR (valence shell electron pair repulsion) theory, the study also computed the formal charges, oxidation states, and molecular shapes of Group III compounds. The findings indicated that Group III elements predominantly form compounds with a +3 oxidation state by relinquishing all three valence electrons; however, certain elements may also yield compounds with a +1 oxidation state by losing just the np electron. Additionally, the results highlighted that Group III elements can create various types of compounds with differing bond types and polarities, influenced by the electronegativity and valence of other atoms. The study further revealed that the reactivities and applications of Group III elements vary based on their bonding characteristics and oxidation states. Lewis structures are useful for understanding the bonding and reactivity of Group III elements and related compounds, according to the study's overall findings. Nonetheless, it is important to acknowledge the limitations of Lewis structures, which include their inability to accurately represent the true shape of molecules, to account for resonance or hybridization, and to provide precise data on bond lengths and angles. Therefore, additional approaches and strategies, like valence bond theory or molecular orbital theory, might be used to improve and confirm the results of this investigation.

Keywords: Configuration, properties, Group III elements, periodic table

***Author for Correspondence**
Victor Chukwuemeka Ukpaka
E-mail: peter.ukpaka@ust.edu.ng

[1]Professor, Department of Chemical/Petrochemical Engineering, Rivers State University Port Harcourt, Rivers State, Nigeria
[2]Research Student, College of Allied Medical Sciences, Department of Pharmacy, Lyceum of the Philippines University Cavite, Philippines
[3]Research Student, College of Engineering, Computer Studies and Architecture, Department of Industrial Engineering, Lyceum of the Philippines University Cavite, Philippines
[4]Research Student, College of Engineering, Computer Studies and Architecture, Department of Computer Engineering, Lyceum of the Philippines University Cavite, Philippines

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INTRODUCTION

Group III elements, located in the third column of the periodic table, include scandium, yttrium, lutetium, and lawrencium. These elements possess three valence electrons in their outermost shell, typically resulting in the formation of compounds with a +3 oxidation state by losing these electrons. Nonetheless, some can also achieve a +1 oxidation state by losing just one electron from the p orbital. The electron configuration of Group III elements is pivotal in determining their chemical properties and reactivity [1]. Found in the p-block of the periodic table, particularly in Period 2 and Group 13, these elements exhibit a uniform valence electron configuration characterized by three valence electrons in the outermost p orbital [2]. This arrangement, represented as ns^2np^1, where 'n' denotes the principal quantum number, is fundamental to their interactions with other substances in compound formation.

The configuration of electrons in the valence shell significantly influences how these elements interact with other substances, facilitating compound formation. With three valence electrons, Group III elements are predisposed to lose these electrons to attain a stable configuration similar to that of the previous noble gas. As a result, they readily produce cations with a +3 oxidation state [3]. The group's related chemical properties are a result of its similar electron configurations.

Understanding the complex interplay between the electron structure and chemical behavior of Group III elements is critically important for various fields, including materials science, electronics, and industrial chemistry. Extensive research has been conducted to explore the connections between electron arrangements and the wide range of compounds that can be synthesized from Group III elements, thereby enhancing the overall understanding of their reactivity.

This small project will investigate the connection between Group III elements' electron structure and chemical behavior, with particular attention to boron (B), aluminum (Al), gallium (Ga), indium (In), and thallium (Tl). The study will look at these elements' electron configurations and how they affect reactivity and other chemical characteristics. The five main Group III elements—boron (B), aluminum (Al), gallium (Ga), indium (In), and thallium (Tl)—are the exclusive focus of this mini-project. It will not cover laboratory-produced synthetic elements like nihonium (Nh) and flerovium (Fl), nor will it cover rare-earth elements commonly associated with Group III, such as scandium (Sc), yttrium (Y), lanthanum (La), and actinium (Ac).

The physical and chemical properties of Group III elements are influenced by various factors, including atomic size, electronegativity, hybridization, and stability of oxidation states. These factors are shaped by periodic trends and lanthanide contraction. Cotton et al.’s "Advanced Inorganic Chemistry" is a valuable resource for discussing these properties [4]. It provides a comprehensive and up-to-date analysis of the fundamentals and uses of inorganic chemistry, covering topics like the structure, bonding, reactivity, spectroscopy, and magnetism of Group III elements and their compounds. This text illustrates how atomic size impacts ionization energies, ionic radii, coordination numbers, and lattice energies [5].

Another important work is "Chemistry of the Elements" by Greenwood and Earnshaw [6], which provides an authoritative overview of the chemistry of all elements in the periodic table, including their history, occurrence, isolation, extraction, uses, and compounds. This book emphasizes how the electronegativity of Group III elements influences bond polarity, bond strength, acidity, basicity, and solubility [6].

A journal article by Evans and Ziller examines recent developments and challenges in the synthesis, characterization, and reactivity of scandium complexes and compounds [7]. Scandium stands out among Group III elements due to its distinctive electronic structure and coordination chemistry, and this article discusses its ability to form complexes with various ligands across different oxidation states and geometries [7].

Additionally, Zhang et al. [8] in their article "Bonding, structure, and mechanical stability of 2D materials: The predictive power of the periodic table," investigate the potential of molecular orbital theory for designing innovative two-dimensional materials based on Group III elements and others in the periodic table [8]. Two-dimensional materials, characterized by a thickness of one or a few atoms, exhibit remarkable physical and chemical properties distinct from their bulk counterparts. This article forecasts the bond order, bond length, bond angle, Young's modulus, Poisson's ratio, and fracture strain for various two-dimensional materials derived from Group III elements [8].

Among the literature available, websites like WebElements Periodic Table offer interactive and user-friendly online access to information on all elements within the periodic table. This resource displays essential data such as atomic number, atomic weight, density, melting point, boiling point, electronegativity, ionization energy, electron configuration, oxidation states, isotopes, crystal structure, thermal conductivity, electrical conductivity, and magnetic susceptibility for each element.

Another valuable resource is Chemistry LibreTexts, which provides an open-access online textbook encompassing various chemistry topics at multiple levels. This site explains how to utilize Lewis structures, VSEPR theory, acid-base theory, and redox theory to represent and predict the shape, polarity, acidity, basicity, and reactivity of various compounds involving Group III elements.

A review of existing literature indicates that the physical and chemical properties of Group III elements are significantly affected by their electronic structure of ns^2np^1, which grants them three valence electrons in their outermost shell. The following summarizes findings on the physical and chemical properties of Group III elements:

- *Melting and Boiling Points:* Because of their weaker metallic bonding, Group III elements often have lower melting and boiling points than other metals. These points decrease down the group as the atomic radius increases and metallic bonding weakens. For instance, scandium has a melting point of 1541°C, while lutetium reaches 1652°C [9]. The boiling points are similarly lower for scandium at 2836°C and lutetium at 3402°C [10].
- *Densities:* Group III elements, particularly gallium and thallium, have low densities, with the latter being less dense than water. Densities tend to increase down the group as atomic mass rises and atomic volume decreases. For example, scandium has a density of 2.99 g/cm^3, while lutetium's density is 9.84 g/cm^3 [9]. Gallium has a density of 5.91 g/cm^3, while thallium's density is 11.85 g/cm^3 [10].
- *Electrical and Thermal Conductivities:* Because of the unbound electrons in their metallic structure, Group III elements have strong electrical and thermal conductivities. These conductivities tend to decrease down the group as the number of valence electrons diminishes and interatomic distances increase. For instance, scandium has an electrical conductivity of 1.8×10^6 S/m, while lutetium's conductivity is 1.6×10^6 S/m [11, 12]. Thermal conductivities are reported as 15.8 W/mK for scandium and 16.4 W/mK for lutetium [12].
- *Ionization Energies and Electronegativity:* Group III elements exhibit low ionization energies and electronegativities, indicating their electropositive nature and tendency to lose electrons during chemical reactions. Ionization energies and electronegativities increase across Period 3 and decrease down Group III, correlating with increasing nuclear charge and decreasing atomic radius. For example, the first ionization energy for scandium is 631 kJ/mol, compared to argon's 1520 kJ/mol, and lutetium's first ionization energy is 523 kJ/mol [10]. Scandium's electronegativity is 1.36, while argon's is 3.20, and lutetium's is 1.27 [10].
- *Oxidation States and Reactivity:* Group III elements typically form compounds with a +3 oxidation state by losing all three valence electrons, although some can also form +1 oxidation state compounds by losing just the np electron. The stability of the +3 oxidation state diminishes down the group due to the increasing size and shielding effect of inner electrons, making it more challenging to remove outer electrons. Conversely, the +1 oxidation state becomes more stable down the group due to the inert pair effect, which facilitates retention of the ns^2 electron pair. Group III elements are highly reactive metals and strong reductants; however, their reactivity declines down the group as the stability of the +3 oxidation state increases. They react with water to yield hydrogen gas and metal hydroxides, although this reactivity also lessens down the group for similar reasons. Additionally, they react with acids to generate hydrogen gas and metal salts, with decreasing reactivity down the group, and can react with bases to form metal complexes or hydroxo complexes, contingent upon the solution's pH [12].

MATERIALS AND METHODS

Materials

Five elements from Group III—boron, aluminum, gallium, indium, and thallium—were selected, along with five representative compounds for each element, including trihalides, oxides, hydroxides, boranes, and aluminosilicates. The atomic and molecular structures, electronic configurations, and the physical and chemical properties of these elements and their compounds were sourced from authoritative references, such as "Group 3 Element" [9] "Group 3 Elemental Properties" [12] and "Boron, Aluminum, and the Group 3A Elements"[13].

Research Method

The methods employed to investigate the bonding and reactivity of Group III elements can be divided into two primary categories: experimental and theoretical. Experimental techniques encompass the synthesis, characterization, and analysis of Group III compounds utilizing various instruments such as mass spectrometry, infrared spectroscopy, X-ray diffraction, nuclear magnetic resonance, and electrochemistry, among others. In contrast, theoretical methods leverage mathematical models, computational algorithms, and software to simulate, predict, and interpret the electronic structure, molecular geometry, bonding energy, chemical reactivity, and other characteristics of Group III compounds. This study will adopt a theoretical approach known as the Lewis structure method.

Lewis structures provide a visual representation of the valence electrons and bonds within a molecule. They can effectively illustrate the distribution of electron pairs, formal charges, oxidation states, and molecular geometries of Group III compounds. For instance, Lewis structures were utilized to analyze the formation and breakdown of organometallic compounds containing Group III elements, such as R_3B (where R represents an alkyl or aryl group), by adhering to straightforward rules and conventions for constructing Lewis structures [14].

Rationale and Justification for Choosing the Lewis Structure Technique

The reasons for selecting the Lewis structure technique are outlined below:

- Lewis structures offer a straightforward and practical method for depicting valence electrons and bonds in a molecule, aiding in the understanding of atomic arrangements and connections, as well as electron sharing or transfer in compound formation.
- They facilitate the determination of formal charges, oxidation states, and molecular shapes of atoms and molecules, all of which influence the physical and chemical properties, such as polarity, reactivity, stability, and solubility.
- Lewis structures allow for the comparison of similarities and differences among various Group III elements and compounds. For example, it is observable that Group III elements typically form compounds with a +3 oxidation state by losing all three valence electrons, although some can also achieve a +1 oxidation state by losing just the np electron. Furthermore, the nature of the compounds formed by Group III elements varies based on bond types and polarities, which are determined by the electronegativity and valence of other atoms involved.
- The ease of drawing and interpreting Lewis structures, guided by simple rules and conventions, makes them accessible. They require only knowledge of the valence electron count for each atom, which can be acquired from the periodic table. The use of symbols, dots, and lines to represent atoms, electrons, and bonds simplifies understanding and visualization.
- Lewis structures are widely recognized and utilized in the field of chemistry, serving as an effective educational tool for teaching and learning fundamental concepts related to molecular structure and bonding. They also integrate well with other methods and theories, such as VSEPR theory, molecular orbital theory, and valence bond theory, which can provide additional insights into the electronic structure and geometry of molecules.

VSEPR theory is a model that elucidates how molecular shape is influenced by repulsion between electron pairs surrounding a central atom. Lewis structures provide a visual representation of the valence

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electrons and bonds within a molecule. The phrase "valence shell electron pair repulsion," or VSEPR for short, refers to the tendency of electrons in an atom's outermost shell to separate as much as possible. Predictions about molecular geometry and bond angles can be made by knowing the quantity and kinds of electron pairs that surround the core atom.

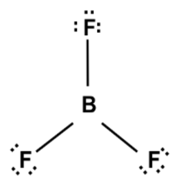
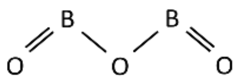
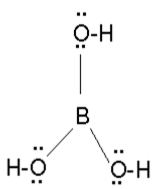
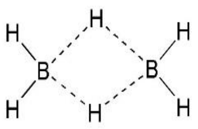
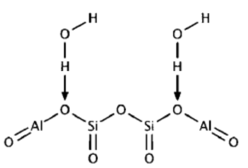
In summary, the Lewis structure method was chosen for this study due to its simplicity, convenience, informativeness, comprehensiveness, and widespread acceptance as a means of illustrating electron pair distribution, formal charge, oxidation state, and molecular shape for Group III elements and their compounds.

RESULTS AND DISCUSSION

Lewis structures provide a visual representation of the valence electrons and bonds within a molecule. The following is a summary of the study's results using the Lewis structure method:

- The Lewis structures for the selected Group III compounds (trihalides, oxides, hydroxides, boranes, and aluminosilicates) were constructed in accordance with the procedural steps outlined in the materials and methods section. Lewis structures provide a visual representation of the valence electrons and bonds within a molecule. Using the accepted standards of Lewis structures and VSEPR theory, the formal charges, oxidation states, and molecular morphologies of the Group III compounds were assessed. The outcomes of the Lewis structure method are summarized in Table 1.
- The results of the Lewis structure method were analyzed and we found some patterns and variations in the bonding and reactivity of Group III elements and their compounds.

Table 1. Lewis structures for the some selected group III compounds.

Compound	Lewis Structure	Formal Charge	Oxidation State	Molecular Shape
BF_3		B = 0, F = 0	B: +3, F: -1	Trigonal planar
B_2O_3		B = 0, O = 0	B: +3, O: -2	Trigonal planar
$B(OH)_3$		B = 0, O = 0, H = 0	B: +3, O: -2, H: +1	Trigonal planar
B_2H_6		B = 0, H = 0	B: -1, H: +1	Trigonal planar (bridged)
$Al_2Si_2O_5(OH)_4$		Al = 0, Si = 0, O = 0, H = 0	Al: +3, Si: +4, O: -2, H: +1	Tetrahedral

Some of the observations made are as follows:

i. Lewis structures provide a visual representation of the valence electrons and bonds within a molecule. Group III elements often lose all three valence electrons to produce compounds with a +3 oxidation state. This is consistent with their electronic configuration of ns^2np^1, which gives them three valence electrons in their outermost shell. The +3 oxidation state is also more stable than the +1 oxidation state for most Group III elements, except for thallium.
ii. Group III elements form trihalides with halogens (F, Cl, Br, I), which are highly electronegative and can accept electrons from Group III elements. The trihalides have a trigonal planar molecular shape and a polar covalent bond type. Lewis structures provide a visual representation of the valence electrons and bonds within a molecule. For example, BF_3 has a higher bond polarity than BI_3, because F is more electronegative than I.
iii. Group III elements form oxides with oxygen (O), which is also highly electronegative and can accept electrons from Group III elements. The oxides have a trigonal planar molecular shape and a polar covalent bond type. As the difference in electronegativity between Group III elements and oxygen rises, so does the bond polarity. For example, BO_3 has a higher bond polarity than TlO_3, because B is more electropositive than Tl.
iv. Group III elements form hydroxides with water (H_2O), which is a polar molecule that can act as both an acid and a base. The hydroxides have a trigonal planar molecular shape and a polar covalent bond type. As the electronegativity difference between oxygen and Group III elements increases, so does the bond polarity. For example, BOH_3 has a higher bond polarity than $TlOH_3$, because B is more electropositive than Tl.
v. Group III elements form boranes with hydrogen (H), which is a non-metal that can share electrons with Group III elements. The boranes have a trigonal planar molecular shape and a nonpolar covalent bond type. The bond polarity decreases as the electronegativity difference between Group III elements and hydrogen decreases. For example, BH_3 has a lower bond polarity than TlH_3, because B is more electronegative than Tl.
vi. Group III elements form aluminosilicates with silicon (Si), which is a metalloid that can share electrons with Group III elements. The aluminosilicates have a tetrahedral molecular shape and a nonpolar covalent bond type. The bond polarity decreases as the electronegativity difference between Group III elements and silicon decreases. For example, $Al_2Si_2O_5(OH)_4$ has a lower bond polarity than $Tl_2Si_2O_5\ (OH)_4$, because Al is more electronegative than Tl.

Therefore, the electronic structure of Group III elements affects their physical and chemical properties in the following number of ways:

- Because of their poor metallic bonding, Group III elements have lower melting and boiling temperatures than other metals. As the atomic radius grows and the metallic connection weakens, the melting and boiling points drop down the group.
- Group III elements have low densities, especially gallium and thallium, which are less dense than water. The densities increase down the group, as the atomic mass increases and the atomic volume decreases.
- Additionally, because of the unbound electrons in their metallic structure, Group III elements exhibit strong electrical and thermal conductivity. As the interatomic distance increases and the amount of valence electrons drops, the electrical and thermal conductivities decrease down the group.
- In addition, Group III elements are electropositive and have a tendency to lose electrons in chemical reactions due to their low ionization energies and electronegativities. As the atomic radius falls and the nuclear charge increases, the ionization energies and electronegativities decrease down Group 3 and increase over Period 3.
- Lastly, depending on the valence and electronegativity of the other atoms, Group III elements can create a variety of compounds with a range of bond types and polarities. For instance, Group III elements can receive electrons from halogens, which are strongly electronegative, to generate trihalides. The trihalides are polar covalent bonds with a trigonal planar molecular structure. As the difference in electronegativity between Group III elements and halogens grows, so does the bond polarity.

CONCLUSION

The distribution of electron pairs, formal charges, oxidation states, and molecular geometries of Group III elements and their compounds were represented in this study using Lewis structures. Following accepted guidelines and norms, Lewis structures were produced for the selected Group III compounds, which include trihalides, oxides, hydroxides, boranes, and aluminosilicates. Lewis structures and VSEPR theories were also used to evaluate the formal charges, oxidation states, and molecular shapes of these compounds. The findings indicated that Group III elements typically form compounds with a +3 oxidation state by relinquishing all three of their valence electrons. This behavior aligns with their electronic configuration of ns^2np^1, which provides them with three valence electrons in their outer shell. For most Group III elements, except thallium, the +3 oxidation state is more stable than the +1 oxidation state.

Moreover, the study revealed that Group III elements can create various types of compounds characterized by distinct bond types and polarities, influenced by the electronegativity and valence of other atoms. For instance, when Group III elements bond with highly electronegative halogens to form trihalides, these compounds exhibit a trigonal planar geometry and polar covalent bonds. The polarity of these bonds increases with the electronegativity difference between Group III elements and halogens.

The study also showed that Group III elements' reactivities and uses differ according to their oxidation and bonding states. For instance, boron and hydrogen can combine to generate boranes, which are nonpolar covalent molecules with potential applications in catalysis and hydrogen storage. Additionally, boron and silicon combine to form aluminosilicates, which are nonpolar covalent substances that can be used in ceramics and glass.

Lewis structures are a useful tool for understanding the bonding and reactivity of Group III elements and their compounds, as this study demonstrated. It is crucial to recognize Lewis structures' drawbacks, too, such as their incapacity to faithfully depict molecular geometries, disregard for resonance or hybridization, and inability to give exact details on bond lengths and angles.

As a result, it is prudent to investigate several approaches and strategies, like valence bond theory or molecular orbital theory, to support and validate the findings of this investigation. Additionally, investigating other Group III compounds, such as intermetallics or organometallics, is recommended to enhance the understanding of the chemistry associated with Group III elements.

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