WHERE IS THE HYDROXYL GROUP IN THE AMMONIA MOLECULE? A GREEK HIGH-SCHOOL CONQUEST.

Anastasia Ioannidou[1], Eleni Kaminioti[2], Stamatia Bachtsiavani[3], Anna Pachatouridou[4], Pericles Akrivos[1]

[1]Aristotle University of Thessaloniki, Department of Chemistry, P.O.Box 135, GR-541 24 Thessaloniki, Greece

[2]Gymnasio Agras, GR-811 05 Lesvos, Greece

[3]1st Geniko Lykeio Xanthis, GR-671 00 Xanthi, Greece

[4]2nd Geniko Lykeio Katerinis, GR-601 00 Katerini, Greece

Abstract

Electrolyte solutions are discussed in every chemistry educational program and their constitution and behaviour are studied in relation to other basic aspects of chemistry, such as stoichiometry, solution concentration and reactions, with special interest in neutralization and chemical equilibrium. Like every other topic related to science teaching and understanding, electrolyte solutions are not free from misconceptions. Unfortunately, several of these misconceptions originate from the form in which the related chapters are written in the textbooks or the manner in which their content is presented by the teacher and in several instances from the whole structure of the chemistry-oriented education program. Indeed, in a recent study we came across certain difficulties faced by undergraduate students in manifesting the basic nature of ammonia. Since it is known that early acquired knowledge plays a major role in determining the quantity and quality of later additions through teaching and experimenting, we undertook the current survey among high-school students for which a limited introductory teaching on bases takes place. In view of the results obtained we propose some simple amendments to the secondary education curriculum which could benefit the apprehension of basic character aspects and report the comments received by a group of post-graduate students and Ph.D. holders in Chemistry.

Keywords: *ammonia, acid-base theories, high-school curriculum*

1. INTRODUCTION

Teaching science is a complex process which has to take into consideration both the established scientific truth and the pre-existing conceptions of the young students and has to be navigated through an everchanging landscape of mental models and their subsequent more detailed and more concise mental models which emerge following the appropriate conceptual changes (Wu and Yiezierski 2023). Detailed and sound reasoning has also to be taught and followed strictly thereafter, in order for the new constructed models and the relevant mental processes to be organically incorporated into the frame of the existing scientific knowledge of the students. When this is achieved by means of suitable teaching strategies (Tekkaya 2003), the newly acquired knowledge is smoothly incorporated into the cognitive background of the students, becoming in this sense meaningful knowledge that can be further expanded to form a uniform understanding of the scientific principles governing the world. Thereafter, the students should be able to apply scientific aspects in situations occurring in their everyday life and make decisions according to the requirements and postulates of science, as they are supposed to have achieved scientific literacy (Bybee 1997, Shwartz et al 2005).

Teaching Chemistry is somewhat more difficult and demanding than the rest of the sciences, since it involves more than just what can be perceived by the senses and/or be amenable to exact measurement. Dealing with chemical phenomena involves more parameters than, for example, trying to understand if a table pushes back a pot placed on it, or even approach the more abstract idea of the application of the Mendel laws of inheritance which can be suitably experimented upon in a classroom. It has been proposed and verified that there may be considered three distinct ways of describing and understanding chemical phenomena, namely the macroscopic, sub-microscopic and symbolic (Johnstone 1991). A chemical reaction may be carried out in a laboratory or a suitably converted bench in a classroom, the reactants may be weighed accurately and the apparent changes, mainly in colour and overall appearance recorded, however, when time comes to provide an acceptable explanation, the situation becomes more complex. First, the teacher has to introduce the chemical nomenclature and explain to some extend the basics of the mass conservation principle. To his aid comes the technique of balancing chemical equations which are used to provide understanding of the process studied (Taber 2009). Understanding the difference between chemical reaction as a phenomenon and chemical equation as a means to describe it proves to be a major obstacle in the above understanding process (Papadopoulos et al 2022). Furthermore, even if this distinction is made clear it cannot always prove to be a useful tool in understanding chemical change. This symbolic language of Chemistry is usually applied by teachers in order to form a bridge between the macroscopically observed chemical reaction and the sub-atomic world to which the discussion has to lead. Useful and meaningful teaching involves the fluent use of all three pathways leading to chemical understanding by the teacher and their adoption and understanding of the students in the classroom (Johnstone 2000). However, special care has to be taken during the initial stages of chemical literacy since it is a well-documented fact that preconceived naïve formulae and stereotypes are firmly bound to the brain of young students (Savion 2009). Further knowledge acquired during the course of an educational program is readily accepted and incorporated into the student's scientific background if and only if it lies along the lines drawn by the existing preconceptions, being rejected if it does not do so. In this respect, knowledge that has been accumulated during the early childhood or in the initial stages of scientific education, tends to establish itself as the scientific truth and will not be affected by later teaching, almost irrelevant to its depth and width of coverage of the specific topics taught (Kontopoulou et al 2017).

Acids and bases form two large groups of compounds which have been encountered and recognized by mankind from an early period but without the knowledge of the underlying principles determining the acidic or basic character of each compound. Most of the aqueous solutions present around or inside our bodies contain acids or bases and it would be desirable to know which type of compounds prevails and to what extent. Acids and bases are used as suitable examples in the discussion of chemical equilibrium, whereupon the introduction of the Brønsted theory of conjugate electrolytes is introduced (Brønsted 1923) as well as in several other reactions, including redox ones. Any reference to a reaction carried out under stable pH is directly connected to the preparation of a buffer solution which requires the use of a weak electrolyte and its physicochemical characteristics are related to the ionization of this weak electrolyte. Therefore, acids and bases form a subject that cannot be omitted from any descent chemical education program. Of course, misconceptions are present in this specific part of chemistry and they have been identified and categorized accordingly (Kind 2004, Horton 2007). Most of these misconceptions are related to acids but it does not mean that the nature of bases is better understood, on the contrary, the lack of several base-oriented misconceptions is related to the limited amount of space in the textbooks and limited time taken by the teacher to discuss bases in the classroom. In Horton's epitomal work, apart from the misconceptions related to neutralization, problems referring to bases are less than half of those related to acids. The same is true for several other reviews on acid/base conceptions of students, in most cases the reference to acid or acidic exceeds those to base or basic by a factor of at least three (Lin and Chiu 2007). In detailed studies as early as 1986 it was observed that undergraduate students knew much more about acids than about bases and, in fact, when asked to do so, they could only remember the names of only two bases (Cros et al 1986, Cros 1988). In a later study (Hand and Treagust 1991) identified several key misconceptions concerning acids and bases, of which only one was connected to bases and that one, also in an indirect manner since its formulation as "a base is something that makes up an acid" certainly is derived from a misinterpretation of the conjugate acid-base pairs in the theory of Brønsted and Lowry.

Limited discussion in the classroom and even more limited experimentation, accompanied by almost no exercise or problem related to bases contributes to minimal understanding the significance of this group of compounds. To many undergraduate students, bases are simply the compounds used to neutralize acids the rest of their chemical behaviour being overlooked. Tracking of the points in the secondary education curriculum where additions, corrections or even reformations could help student form a more solid background in understanding the nature and behaviour of bases seems therefore something desirable and something that work has been done on and should continue to be done.

2. THE CURRENT STUDY

2.1 Background

The current study was prompted by an analogous one carried out on undergraduate students majoring in Chemistry (Kaminioti et al 2024). In that study a simple question requiring the substantiation of the basic character of ammonia within the frame of the known electrolyte theories revealed a large gap in the understanding of the concept of base and a limited one of the relative importance and interconnection between the existing electrolyte theories. The well-documented inability of undergraduate students to handle chemical equations (far more so when they are required to device one in accordance with a definition they state properly) proved to be a major problem. However, it was also apparent that their much longer acquaintance with the Arrhenius theory of electrolytes (Arrhenius 1884) tends frame it as the central or even the sole acceptable theory of electrolyte solutions. It was both frustrating and interesting to note that some final year undergraduate students could only remember the Arrhenius definition for a base although they are taught on several occasions (within courses in General and Inorganic Chemistry, Organic Chemistry, Biochemistry) about the Lewis theory (Lewis 1923) and its applications. This is not unique to Greek students or is not limited to the understanding of chemical concepts but is related to the scientific literacy steps proposed, indicating that the students under consideration have not reached the structural (conceptual and procedural) level (Bybee 1997). Prior to this level, the students may use the scientific vocabulary in the proper manner, and give the correct form of definitions and maybe formulae but they can only memorize them and also memorize responses to questions.

2.2 Overview of the Greek educational system

In the Greek educational system, the compulsory stage consists of six years of primary school followed by three years in junior high-school (termed Gymnasio). Following it comes a three-year span of studies in senior high-school (termed Lyceio) after which, the scores each student achieves in nationwide examinations determines whether the specific student will continue studies to some higher education institute. Of course, different criteria and different examinations are taken for specific cases, students aiming at majoring in science or medicine have to take examinations on Chemistry while the rest are not required to do so. In this respect, students majoring in Chemistry, Physics or Pharmacy have followed the whole of the secondary education program for Chemistry. Acids and bases (as the titles of the relevant textbook chapters have it) form a part of this body of knowledge, which is introduced to the students in several steps, which are not simply or smoothly distributed within the Secondary Education Program. Indeed, reference to acids and bases is first made during the second year of junior high-school (student age 13-14 years) and only in general terms and without reference to any relevant chemical equation as the approach during this part of the education program is mainly descriptive and observational. Of course, following the Occam razor doctrine, the simpler Arrhenius theory is the only one discussed to some extent. Up to this point this seems both acceptable and appropriate since it consists of the first experience of the students in the field and, furthermore aqueous solutions will be used in any related laboratory experiment. In the next and final year of junior high-school and the compulsory educational program, reference is made again to electrolytes with the one-phrase repetition of the Arrhenius definition of bases as compounds which, upon dissolution in water produce hydroxide anions. In a short table supporting the above there are presented four metal hydroxides as well as ammonia, for which, the typical hydrolysis reaction which is responsible for the production of the desired hydroxide anions replaces the molecular formula used for the alkali metal hydroxides. There is also suggested, execution of an experiment on electrolyte solutions which is dealing with the acidic behaviour of dilute acid solutions and a correlation of the pH scale with the acidity of a solution.

The content of the chemistry curriculum takes a drastic turn in senior high-school where acids and bases appear again in the first and third year (student ages 15-16 and 17-18 respectively). In a half page content in the first year's textbook, the Arrhenius definition is given again as well as indication that bases are almost exclusively metal hydroxides with the notable exception of ammonia, for which the following "ionization reaction" is given.

$$NH_3 + H_2O \rightarrow NH_4^+ + OH^-$$

There appears also a statement that bases may be categorized as strong or weak, the example for weak bases being again ammonia.

The backbone of the third year senior high-school course is chemical equilibrium and in this context introduction of the Brønsted theory seems appropriate aiming at the understanding of relative weak and relative strong acids and bases. Little effort is placed, however, in identifying Brønsted bases, especially when they cannot be considered as Arrhenius bases as well. Lewis's theory is just referred to but not described at all. However, Lewis's theory is among the basic topics covered in the introductory undergraduate course of General and Inorganic Chemistry since it is prerequisite to the writing of molecular formulae and derivation of hybridizations and therefore local structures of simple compounds (Papadopoulos et al 2022).

2.3 Execution of the investigation

The question was given to the students as part of a regular test during a teaching hour in the classroom, after the relevant chapter of the textbook had been completely discussed. For students in the first and second year of studies in the senior high-school the question was simply put forward as a requirement to substantiate the basic character of ammonia and an additional clarification was that a chemical equation which could be used to manifest this character was desirable. At that point of the secondary educational program the students are acquainted with only few chemical equations, one of which is the hydrolysis of ammonia. For the third-year students there was a slight difference in the phrasing of the question since they were asked to substantiate the basic character of ammonia according to the known acid-base theories, implying that they should have to report all the theories known to them. A group of nine persons, expert in the field of teaching Chemistry, consisting of teachers in high-schools and members of the staff of the local Chemistry Department verified that the complete answer should include the names of the three originators of the three theories known to the students, a brief but accurate description of the definition of a base for each theory as well as a simple chemical equation describing the basic nature of ammonia. Since it is known that students at this age are not capable of devising their own chemical equations even when they are verbally described to them, compensation was made that the typical hydrolysis of ammonia equation would be acceptable for every theory, provided that indication was made about which part of it manifests the basic character of ammonia according to the specific theory, as presented in Figure 1.

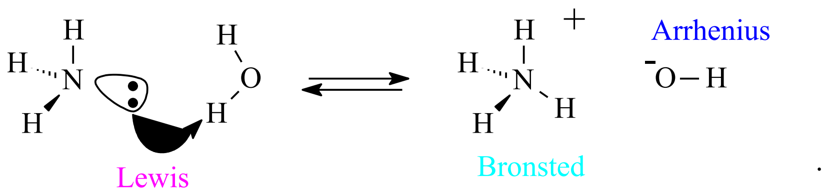

Figure 1. General scheme manifesting the basic character of ammonia in the three acid-base theories.

The study was carried out on students from four different schools distributed in Northern Greece with sample sizes 39 for first year and 99 for third year senior high-school students respectively.

3. RESULTS AND DISCUSSION

In view of the above, it was not surprising that a total of 76.9% of the first-year students did not attempt to produce a chemical equation and that a further 17.9% gave a wrong one. The surprise was that 53.8% of the students could not give the right definition of bases according to the only theory known to them, leaving only a 7.7% to do so. An important finding, which we shall not comment extensively upon since the total sample is limited to 39 almost equally balanced between boys and girls, is that the only right answers were given by girls. Some of the erroneous answers merit discussion, however, notably the justification of the basic character of ammonia because it neutralizes acids. It is common place to set up an easy and simple experimentation, as several teachers do, where litmus paper is used to reveal the acidic behaviour of a solution and then the pH shift as ammonia is added dropwise to the solution. This is in agreement with a widespread belief that bases are the substances that neutralize acids (Horton 2007). There is even a wild statement, coming from a misconception that was created most probably within the classroom with the unintended aid of the teacher. In several cases it is known that young students get confused in the process of building their mental models in order to identify acids and bases (Yalcin 2011). Teachers therefore, try to device some empirical rules for their students and it is a general trend to categorize acids as the compounds with H preceding the rest of the atom symbols in the formula, in line with the convenient way of placing the positive part of an inorganic compound in front of the negative one. In response to student inquiry why KOH for example is not considered an acid, a simple but unjustified answer may be that in its formula the H atom is at the end. This is exactly the response that we got from one student, namely that ammonia is a base because its hydrogens are written at the end of its formula.

The situation is more complex in the third year high-school students, since they supposedly have come in contact with three acid-base theories. Of course, the epidermal reference to the Lewis theory does not allow for great expectations as far as its assimilation and in-depth understanding. Therefore, the 8% references to the name of the originator and the 7% of correct citation of the base definition may be considered as significant. The important finding in this part of the survey is that nobody actually failed to give the correct definition, the 97% of the answering sheets were empty at this point, which may be regarded as a strong impact that the theory made to those who cared to read the corresponding passage in the textbook. Of course, nobody was able to present an adequate chemical equation, most probably because there is no reference in the textbook of any strategy to construct such an equation.

Brønsted theory is introduced at this year of studies and therefore, represents the new addition to the scientific background of the students. In our view, it is disappointing that only 38% of the students record the name and less than half of those gave a sufficient definition, while, about one third of the 42% who gave the corresponding definition, did not connect it with a name. This may serve as an indication for the need of revising the way the theories are presented and a prompt to definitely state the name of the originator of every theory, at the same time making note of the existence of other theories as well. In our belief again, the rather discrete presentation of the Arrhenius theory at an early stage, without any indication that it is the oldest or more widespread theory, sets it at the position of the sole acid-base theory, therefore, when time comes for the introduction of the Brønsted theory, students tend to believe that it is either a variation or simply the same as the theory they believe they know already and since the definitions of acids in the two theories do not differ dramatically, at least as the verbal part is concerned, the difference in the base definition tends to be overlooked.

4. PROPOSALS

In view of the above observations, it seemed reasonable to consider some simple and easy steps that could be taken towards minimizing the misconceptions and maximizing the understanding about bases. It seems that bases are overlooked since they are discussed much less than acids. Of course, one cannot invert the importance of the two groups of compounds, however, textbooks could easily incorporate small paragraphs or reform existing ones to indicate that not all compounds bearing H atoms are acids, that bases may also contain H atoms, not necessarily in OH groups etc. Furthermore, when problems are presented to the students to work on, at least one could be related to bases. Especially for Greek textbooks, the chapter discussing electrolytes, labelled "Οξέα και βάσεις" (Acids and bases) could be renamed as "Βάσεις και οξέα" since the initials of the words are found in this sequence in the Greek alphabet. In this respect, bases will have to be discussed first and then a larger period of time and space in the textbook may be devoted to the description of acids, enhancing the interest that bases receive in the process.

Final year undergraduate students, postgraduate students of the Department and teachers of high-schools, other than those who participated in the survey were asked about the possible effect of several proposed amendments in the presentation of bases to the secondary education curriculum. The answers were based on a five grade Likert scale ranging from 1= not at all to 5= completely. The responses of 24 persons are summarized below.

Do you believe that the concept of "base" is described well in the secondary education system?

No 4.2%	slightly 16.7%	moderately 33.3%	adequately 33.3%	perfectly 12.5%

Is the coverage of bases adequate for the understanding of the related concepts?

No 4.2%	slightly 33.3%	moderately 25.0%	adequately 25.0%	perfectly 12.5%

In the Greek educational system in general reference to electrolytes is made in the sequence "acids and bases". Given the much-extended coverage of acids students tend to believe that bases are the compounds that are not acidic. Do you agree with this statement?

No 8.3	slightly 12.5	maybe 33.3	a lot 37.5	absolutely 8.3

A rename of the relevant chapter in the textbooks as "bases and acids" would promote better approach to the bases?

No 12.5	probably not 12.5	maybe 50.0	probably yes 12.5	certainly 12.5

In relation to pH, is there enough and definite reference to pOH as well as their interrelation under stp?

No 0.0	rather not 29.2	moderately 29.2	rather yes 33.3	certainly 8.3

It appears, from the inspection of the above responses that, people who have recently gone through the complete chemical education curriculum, believe that bases are described in a proper way but insufficiently, they believe that the curriculum construction is in part responsible for misconception creations but are not sure that a reform of the specific chapter in the textbooks would be desirable. Maybe this reluctance is based on past experience where reform was not towards the desired target or did not produce the expected results.

5. CONCLUSIONS

Description of bases is limited in the Greek secondary education curriculum and young students scarcely come across to problems and never encounter laboratory experiments where bases are used. The theories about acids and bases are presented in a logical but scattered way, ensuring students of the uniqueness of the Arrhenius theory, to the point that they do not recall the name of the originator anymore and then, present the Brønsted-Lowry theory where bases are only reported as conjugate electrolytes to acids. Lewis's theory may not be even mentioned if the teacher of a school does not find time enough to do so. Proposals are made for some simple steps that could amend the situation to some extent but they should require discussion and consent between government officials responsible for determining thr educational policy and teachers at all educational levels.

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