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Shaping of the Stoicheiometry Concept in Secondary Education: Greek Minor Urban Area High Schools

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Abstract

A study is carried out by means of distributing a pair of questionnaires to secondary education students in minor urban areas of Northern Greece. The content of the questions is related to the concept of stoicheiometry (Note 1) as it is presented in the textbooks and described in the Greek chemistry curriculum for secondary education. The two questionnaires were distributed in the beginning and in towards the end of the school year with the scope of mapping the degree of assimilation of the stoicheiometry related concepts by the students. The concept is not introduced to a considerable extent in junior high-school while it is among the main topics addressed in the second grade of senior high-school, when Organic Chemistry is explicitly discussed. The target group therefore, was students of second grade of senior high-schools. The first questionnaire, therefore, serves as exploratory in the determination of the starting point of overall understanding of chemical concepts by the students. The validity of the questionnaires and their efficiency in fulfilling the scope of the current research was carried out by the application of certain post-statistical indices with the final goal being their utilization as a diagnostic tool for probing student understanding of chemical concepts.

Keywords: secondary education, chemistry curriculum, stoicheiometry, questionnaire

1. Introduction

The science of Chemistry aims at the understanding of the material changes in the surrounding world as well as within the human body and expresses the related phenomena in the form of laws and equations connecting observations with abstract ideas. It consists of a series of fundamental anchors on which the “school knowledge” is bulit through teaching in the classroom. Teaching is carried out by persons who have received the corresponding education and follows a predetermined education program which spans over several school years. Regardless of the specific period of time or position on the globe, such an education program includes topics like the corpuscular nature of matter, the evolution of ideas about the structure of the atom, the nature of the various types of chemical bonds, the properties of specific classes of compounds, e.g. acids and bases and the characteristic reactions of specific functional groups. There are several observables as well as abstract concepts related to the above topics and each one demands time and effort from the teacher in order to be assimilated to the cognition background of the students. These efforts include, besides the traditional teaching tools, hands-on experience, problem solving and even computer simulation in order to fulfill their scope.

Among the topics required for a better and complete understanding of Chemistry, stoicheiometry is playing a central role because it is related to several other aspects of Chemistry, especially in the description of the chemical reaction through the rules and constrains for balancing the corresponding chemical equation. It is therefore related not only to molecules themselves but to chemical reactions and even to the outcome of chemical reactions through the formulae used to represent the chemical equilibrium state reached in several of them.

In the early stages of secondary education, the students are required to just remember that the right representation of the water molecule is H_2O and the one for ammonia is NH_3 without any in-depth discussion of the electron configuration of the atom and its relation to the position of each element within the periodicity table.

The relevant knowledge which leads to the understanding of the way that a covalent bond may be formed as well as of how many such bonds a specific atom may form comes at a later stage along with the Lewis theory about electron pairs and their contribution to the stability of atoms and molecules. It is at that stage that some real understanding of the meaning of the numeric coefficients is achieved and is related to the mole itself and to the stoicheiometry of the compounds. It is then that it should be clarified that H_2O is a simple and easily understood abbreviation of H_2O_1 indicating that there are two hydrogen atoms bonded to a single oxygen atom through pairs of electrons which result in the formation of the required doublet of electrons for H and the octet for O respectively.

The mass conservation law which is applied in chemical reaction presentations is relatively easy to teach and to understand since it was proposed at least as early as Lomonosov in the 18^{th} century (Pomper, 1962). The law is strictly followed when writing chemical equations. Several algorithmic processes are utilized to enforce the law and they all lead to the final form of each equation where the numbers for each participating atom on either side of the reaction are set equal. In a typical example, the reaction of hydrogen fluride with chloroform ($CHCl_3$, which is expected to contain the following information: 4 valence electrons for C, 1 for the H atom and 7 for each Cl atom, 4 covalent bonds through which every H or Cl atom completes its outer electron shell completing in the process the octer required for C) produces hydrogen chloride and the fluorochlorinated hydrocarbon which is used as the starting material for the synthesis of Teflon. The specific reaction and its description aim at the long and ever-saught connection of scientific concepts with the real world as its is understood by the non-scientist (Kekauoha, 2018). In a fist approximation the chemical equation may be writen in the form:

$$CHCl_3 + HF \rightarrow CHClF_2 + HCl$$

This presentation only reports in the symbolic language of Chemistry the reactants and the products of the reaction, however, it is not balanced as there appear to be halogen atoms missing on either side of the arrow discriminating between reactants on the left and products on the right.

The balanced form of the equation should have the form:

$$CHCl_3 + 2\ HF \rightarrow CHClF_2 + 2\ HCl$$

It is apparent from the above example that the numeric coefficients preceding the compounds' formulae in the chemical equation enforce both the correct application of the law of mass conservation and the correct molar ratio of the compounds participating in the reaction. These coefficients are also used by students in the process of solving problems where quanitites of reactants or products are required for a given set of quantities of the rest of the chemical species involved. At a subsequent stage coupling of these coeficients with the mole of each compound is used in order to calculate the yield of a reaction and in a subsequent step to determine the equilibrium constant, in the case of reversible reactions. Furthermore, when dealing with reaction kinetics or equilibria (van't Hoff, 1884; Le Chatelier, 1888), the numerical coefficients of the compounds present in a medium are used for the determination of the order of the reaction based on the reaction rate equation. The combination of the reaction rate for the two half-reactions, heading to the right and to the left respectively leads to the formulation of the reaction constant. In both of the above formulae the mass action of each compound is utilized and itself is expressed in the form of the concentration of the compound raised to a power, equal to the syntelesti by which the compound enters the chemical equation. The rate law of the discussed reaction can be formulated as

$$u = k[CHCl_3]^1[HF]^2 \quad (1)$$

from which the order of the reaction may be inferred as the sum of the exponents, i.e. 3, while the equilibrium constant takes the form of

$$K = \frac{[CHClF_2]^1[HCl]^2}{[CHCl_3]^1[HF]^2} \quad (2)$$

The interrelation of stoicheiometry to several key aspects of chemistry places it in the core of chemical knowledge and as such is being taught in every level of education involving the sciences and especially chemistry (Ahtee & Varjola, 1998). The topic is not, of course, free from misconceptions (Kind, 2004; Horton, 2007) and when coupled with lack of mathematical skills may form epistemological obstacles (Bachelard, 1938) to a thorough understanding of the chemical reaction observation, its presentation in the form of a chemical equation and further working on the quantities involved in the reaction in efforts to consume reactants or realize products at the optimum level (Katsikis et al., 2017).

2. Description of the Survey

2.1 Brief Description of the Status Quo

The questionnaires were constructed taking into consideration both the student and the teacher in charge of each class. Previous surveys conducted by several Greek researchers over the last decades have revealed the fact that students generally adopt the least effort pathway in dealing with examinations, avoiding as much as possible extensive descriptions other than the citation of standard rules and laws. Therefore, questions requiring extensive discussion were kept to a minimum. Furthermore, the set of questions were limited so as to require at the most 20 minutes to complete, taking into account the introduction required to be carried out by the teacher (Treagust, 1988). The first questionnaire was exploratory in nature consisting of questions covering a broad spectrum of topics which are taught within the chemistry curriculum of the Greek high-school.

Throughout the successive educational reforms of the Greek high-school teaching program, several affected the sequence and depth or width of chemical concepts taught, however, Chemistry is constantly held to be taught in the junior high-school grades B and C for a single didactic hour per week (Vandoulaki et al., 2016). Furthermore, it is handicapped relative to the other sciences taught since reference to it in mass media information and everyday talk is made only in cases of its unfruitful uses (Karageorgiou et al., 2017). In grade B a broad discussion is conducted about the environment and chemical phenomena and changes within it and the symbols of several elements are presented while there is only one specific reaction mentioned, the one regarding water formation, without discussion of the meaning of the numeric values of subscripts or coefficients involved. In grade C the topics discussed begin with electrolytes, their reactions and the concept of pH, followed by an introduction to the Periodic Law and the classification of elements within the Periodic Table. Specific reference is made to carbon and its compounds. It must be noted at this point that junior high-school is the last stage of the compulsory education in Greece. It is apparent from the above that junior high-school curriculum prefers a width of topics over in-depth investigation of a few central ones. Therefore, students entering the senior high-school regime generally do not possess a solid chemical background. As a consequence, a repetition of everything that has already been taught is carried out during the two hour per week course of Chemistry in senior high-school grade A. The process is atypical example of a spiral curriculum (Bruner, 1960). The seniior high-school curriculum adopts the atoms-first approach in contradiction to the junior high-school process and proceeds from the description of the atom to its electron configuration to the construction of the Periodic Table. Bond formation is described for the first time to the students followed by an introduction to chemical reactions and stoicheiometry to which the concepts of mole, molecular mass and concentration are attached. It is apparent again that the required bredth and depth of the concepts included in the course cannot practically be met resulting in a diminishing of material described and related skills aquired by the students.

2.2 Questionnaire Evaluation

The contents of the questionnaires were evaluated by a group of persons with knowledge of the chemical concepts involved. The reviewers belong to the teaching staff of the Chemistry Department of the Aristotle University of Thessaloniki (three, 3) to secondary education teaching staff (four, 4) and to the post-graduate students of the Department who attend a course on Chemistry Didactics (five, 5). A compass to navigate through the mental actions required to answer the questions was provided by the well-known Bloom taxonomy (Bloom et al 1956), where differentiation is made between knowledge accumulation and skill evolution. The taxonomy recognizies objectives related to acquiring information and to a subsequent level of understanding it. Following are two levels of skill construction, related to the simple application of previously acquired knowledge to standard situations and to its application to a new problem. Since in the taxonomy the four steps are set to be distinct and arranged hierarchically (that is, completion of one is required before moving to the next one in the above mentioned route) we assumed a matching between them and the natural numbers in the form of 1= remembering, 2= understanding, 3= applying and 4= analyzing. The reviewers were asked to determine the distinct mental actions required for answering each question and give a mark to each of them according to the above matching scheme and provide the mean value of the total score over the distinct steps assumed.

Averaging over all the reviewers' answering sheets for each question produced a value for the specific cognition skill level of a question. We may term this simple index as "skill level" of the ith question, S_i. Summation over all the questions resulted in a total of points for the specific questionnaire which in turn produced an average "cognition skill level" required for the questionnaire, which may be presented as CL. A very easy quiz (and correspondingly a very easy question within it) would result in an average total cognition level of approximately 1 while an extremely demanding one would give a number close to 4. The boundaries set by the reviewer group on the questions incloded in the current questionnaires are 1.23 and 2.45 respectively. Questions of the first, preliminary quiz range between 1.23 and 1.91 with an average CL of 1.54, while for the second and more demanding one they range from 1.90 to 2.45 giving an average of 2.17.

A total of about 230 students from 8 different schools located in small urban centres of Northern Greece provided answering sheets which were assessed in the formal manner for in-classroom tests. Of these, 215 were subjected to the susbequent recording and analysis. A wide range of scores were obtained giving, for the first questionnaire an average of 12.91 (on a 0-20 scale) with a standard deviation of 3.86. For the second questionnaire the corresponding values are 9.70 and 4.75. The preliminary quiz was aiming at the defining of the starting point with respect to which the evolution of stoicheiometry concepts understanding could be measured and it is a practice that has helped in analogous efforts before (Kontopoulou et al., 2017). In view of the above cited results is seems that following almost one school year of studying organic chemistry, where reaction stoicheiometry plays an essential role in determining the products and in specific set problems, the constitution of reactant mixtures, the understanding of stoicheiometry has taken a backward step. However, one should take into consideration the more general and less demanding nature of the first test relative to the focused and demanding final test and proceed with the scaling of the results of the two tests. Doing it, in the form of the ratio of their overal congnition skill levels of 2.17/1.54, the mean mark for the second test is re-evaluated as 13.67. It is better however, to accept the fact that a more demanding test better describes the abilities and skills of students and in this respect we proceeded with a saling-down of the scores of the initial test which gave for it a mean of 9.16. When the marking scheme for the test was performed by applying the above-mentioned Bloom-based approach, the mean score was 8.68, which is much closer to the scores in the range 6.5-8.50 realized for analogous studies in Greek high-schools in the last decades .

Table 1. Summary of the studied indices for each question of the final questionnaire

question	**P_i**	**r_i**	**D_i**	**S_i**	**r'_i**
1	0.36	0.48	0.64	1.91	0.49
2	0.69	0.55	0.64	2.27	0.55
3	0.53	0.63	0.79	2.00	0.61
4	0.51	0.59	0.69	2.05	0.60
5	0.56	0.64	0.76	2.32	0.64
6	0.29	0.25	0.31	2.00	0.24
7	0.47	0.39	0.52	2.36	0.40
8	0.48	0.34	0.43	2.45	0.34
average	0.49	0.48	0.60	2.17	0.48

S_i =skill level index, P_i = difficulty index, r_i =reliability index and D_i =discrimination index for each question. The primed index values are obtained from the treatment of the results according to Bloom's taxonomy correction.

Some post-assessment indices were applied to verify the suitability of the questionnaires for reaching sound conclusions for the current population studied. The first and more simple of them may be termed as difficulty index, indicating how many of the students answered correctly each specific question, therefore having the formula.

$$P = \frac{N_i}{N} \qquad (3)$$

where N is the total number of answers and N_i is the number of the correct answers given. It is widely accepted that, values close to the boundaries of 0 and 1 would represent extremely difficult and extremely easy questions respectively; therefore generally the accepted margins for the index value are 0.2 and 0.8 (Eggen et al., 2017).

Following, the reliability of each item and of the test as a whole has to be determined and this is done by the point biserial coefficient, r, which relates the score to each specific item to the total score as

$$r = \frac{\overline{X_i} - \overline{X_o}}{\sigma}\sqrt{\frac{P}{1-P}} \quad (4)$$

where X_o and X_i being the average assessment marks of the whole population and of those who answered correctly the specific question; P being the previously defined difficulty index and σ the standard deviation of the whole population (Kiviniemi et al., 2018). The values of the index are expected to lie above 0.2 with the distance from that limiting value being analogous to the discriminating ability of the question under consideration.

Finally, the discrimination index D, measures the discrimination ability of each test item, usually examining the top 25% and bottom 25% scores through the formula

$$D = \frac{N_H - N_L}{(N/K)} \quad (5)$$

with N_H and N_L being the numbers of the high and low achieving students answering correctly each question and K a numerical factor, which takes the value of 4 in the case where the 25% top and 25% bottom scores are considered (Eggen et al., 2017). The results of the present study are presented in Table 1. In our case the final test could not be used in itself for a reliability test since it could not distributed both at the beginning and at the end of the school year. Therefore, a reliability of the final test in the form of the Ferguson delta which takes into consideration the distribution of the answers obtained was used (Eggen et al., 2017). The requirement is the the delta value be larger than 0.90 and in our case it was calculated to be 0.96.

3. Results and Their Discussion

3.1 Introductory Questionnaire

The results of the first quiz account for the starting point from which the students enter grade B of senior high-school anf provide the basis to better understand their achievements in the second quiz. Regarding the symbolic language of Chemistry, the results are good but not excellent; of the formulae given 87% of the students recognize H_2SO_4 as representing a molecule, 69% do so for NH_3 and 47% for CO, maybe mistaking it for Cobalt, a common misinterpretation, all similar to a study in metropolis and urban area schools (Papadopoulos & Akrivos, 2022). Interestingly an astonishing 73% think that He also represents a molecule. In filling in the missing words in a paragraph describing the layout of the Periodic Table 17.2% gave all the required words, 55.3% filled in at least 6 of the 9 and only 13.9% completed 4 or less. This finding represents, in our belief, a rather good understanding of the periodicity of element properties since the paragraph was not drawn out of a textbook but constructed by us.

A 81% reported the correct electron configuration for element $_{19}X$ out of the four possible configurations provided but only 65% were able to report the correct verbal description of the neutralization reaction out of four provided pairs produced by rearrangements of acid, base, salt and water.

The definition of solutions presents an obstacle to the students in accordance with literature sources (Kind, 2004; Horton, 2007). Inour case only 30% believe that it has to be homogeneous while the majority, 47% think of it as any mixture containing at least two different species and a further 13% that it should contain mainly water. The last of the above ideas has its origin in the use of solely aqueous solutions in the experiments and almost solely in problems discussing solutions. Interestingly enough and contrary to our findings in large city and rural area schools, the current student population was to a great extent able to identify the most dilute solution among the four presented in the order 2%, 4%, 6% and 0.8%. Since the values are few and well defined the finding indicates that the present study students were more devoted to the completion of the test and therefore made the correct readout of the question.

Solution constituents, i.e. solute and solvent, form a group of aspects and words which need explicit introduction by the teacher and intense focus by the students in order to overcome misconceptions. Furthermore, the quantity of a solute expressed as mass is quite different from its concentration in a solution and in view of the timeless confusion of the two meanings we have proposed an appropriate simple form of the typical dilution experiment (Koumoutsi et al., 2018). To clarify misconceptions related to the constituents of solutions the students were asked to determine which property of a non defined aqueous solution would diminish upon adding water to it. Fuerthermore, the quantities of sugar and water contained in 200 g of a 5% w/w aqueous solution were required and in both cases the well-documented misconceptions related probably to the similarly sounding terms of solvent, solute and solvation made their appearance.

3.2 Stoicheiometry Cognition Assessment

The results of the second questionnaire serve as an assessment of the extent to which topics and ideas of stoicheiometry have been integrated into the scientific cognition background of the students. As the grade the participants attended is devoted to Organic Chemistry, the questions presented to them had the related content.

Obtaining the formula of an organic compound based on its percent per weight constitution is worldwide assumed as basic to the understanding of organic chemistry and as such the formula of a hydrocarbon having 80% w/w carbon content was required given a set of four possible compounds. A considerable but not promising 53% of the students made the right prediction. The success percentage is almost identical to a more complex problem where the formula of a saturated alcohol (of the general formula $C_nH_{2n+1}OH$) was required given the mass ratio of oxygen vs hydrogen. In this case 51% of the students provided the correct answer the rest being almost equally distributed among the other three possible answers provided. The findings verify that the stoicheiometric coefficients in a molecular formula and the corresponding mole ration of the atoms are understood to a moderate extent.

Some basic knowledge of stoicehiometry, combined with simple mathematical skills and consistency with the mass preservation law helps to complete and balance any chemical equation. However, in Greek school textbooks fractional coefficients are retained in several cases leading often to miscalculations. The participants were asked to choose among four integer numbers as the sum of the smallest integer coefficients of a chemical equation describing the complete combustion of $C_5H_{12}O$. In our belief, it was a rather simple question, however, only 36% of the students provided the correct answer. It would be of interest, in a subsequent study, to transform the question into an open-type one by removing the contraint of values presented so as to track the possible pathways leading to erroneous results. In a similar question the application of the Avogadro hypothesis was essential to remember and apply since a gaseous alkyne had to be identified based on the fact that its complete combustion produced a fourfold amount of carbon dioxide. Since the coefficients were not required to be integers, the corresponding arithmetic manipulations of the previous question were bypassed and consequently a substantially larger success percent of 69% was realized.

In a further complicated requirement, a mixture of known mass constitution, consisting of two alkanes and two alkenes, was passed through a solution containing excess of elemental bromine and the net weight change of the bromine solution was required. Although the answer only requires summing the weights of the hydrocarbons capable of reacting with bromine, it appears that only 56% of the students can make the distinction in the reactivity of alkanes and alkenes. It is of interest to note at this point that the formulae of the hydrocarbons were given therefore making it easy to identify visualy the unsaturated ones, relating the result to the understanding of the symbolic language of Chemistry.

In another question of analogous complexity, an equimolar mixture of two alkynes were subjexted to complete combustion with a given volume of dioxygen measured under the same conditions and the alkynes had to be identified out of four given pairs. In view of the previous observations, the 48% of correct answers lies within our expectations. Totally expected though, was the fact that only 54% of those who gave the correct answer to the previous question answered correctly this one, indicating that the simple but demanding mathematical skills required for the question under consideration are not as trivial as one might think.

A check for the understanding of simple chemical reactivity was carried out in connection with simple stoicheiometric calculations in a subsequent question where a two-step sequence of reactions was given. The initial compound for which the hint that it was an unsaturated hydrocarbon was subjected to acid hydrolysis and the product formed was heated to produce the final compound for which the percent mass constitution was given. Four triplets of compounds were presented as possible sequences of compounds for the reaction scheme, with a 47% of the students providing the correct answer, while the homologue series of the final product was predicted by a 71%, in complete accordance with the results of a previous study.

A well-known and documented problem that young students face is related to their ability to retrieve information from graphs or pictorial representations. It has been a continuous finding in recent local studies that young students are not acquainted with the pictorial information incoroporated within a text and can only relate one to the other only if certain spatial arrangement of the two is present (Kasiara et al 2019). The chemical equation given was

$$A_2(g) + 3B_2(g) \rightarrow 2AB_3(g)$$

and a reaction box was given with equimolar amounts of the two reactants. The objective was to identify the final stage assuming the completion of the reaction. It was expected that the limiting reactant aspect would be applied and the B_2 molecules would be disrupted at a mental level to provide free B atoms to form as many as possible AB_3 molecules for which the appropriate number of A_2 molecules would have to be disrupted too leaving some A_2 molecules intact. The identification of the limiting reactant is a known and consistent problem (Huddle & Pillay,1996; BouJaoude & Barakat, 2000). A mere 29% gave the expected answer, however, another 26% thought that the remaining A_2 molecules would not be present in the final stage of the reaction and another 29% probably did not identify the initial A_2 molecules as such but rather as atoms of A, giving the corresponding AB_3 molecules and several B_2 molecules as intact. The finding is in accordance with the proposal that when dealing with complex tasks requiring the execusion of several simple tasks it is not straightforward that misconceptions or even mathematical mismanipulations will be carried over from the simple tasks to the complex ones which are composed of these simple tasks (Eylon et al., 1987).

3.3 Further Considerations

Partition of the results was attempted with respect to the sex of the student since it has been argued that it may represent a factor influencing the attitude towards studying science, however, as in a number of analogous surveys we carried out in the past, although at first glance there is a minor advantage to the girls (average score of 9.79 relative to 9.65 for the boys), no statisticaly significant differences were observed between the two groups of students. However, an interesting result emerged, which cannot be detected in the reported data and it has to do with the varying performance of the schools that participated in the study. The differences detected can be attributed to the attitude of the students towards the course and, of course, towards the teacher who is interacting with them. In this respect and following the application of the Bonferroni correction in order to control the familiwise errors, we observed that the three factor levels, representing schools in a metropolitan centre, in small cities and in rural areas are significantly different from each other, all comparisons performed simultaneously (Dunn 1961). In fact all three normalized level means differ from one another by more that the approximate Bonferroni distance and the more precisely computed p values are indicative also of the significant difference between each of the pairs investigated. Returning therefore to the descriptive statistics results, the mean scores of the first questionnaire reveal that the metropolitan city schools participating perform worse than schools in rural areas and those follow ones in medium sized cities. Given this difference in the initial stage it is not unexpected that a similar ordering occurs for the final test results with average scores of 6.15, 7.81 and 9.70 respectively.

4. Conclusions

The idea that the more basic aspects and topics should be presented at an early stage of a curriculum is evident from the overall performance of Greek high-school students. Stoicheiometry, in conjunction with the description of the periodic table and some basic quantum view of the atom is among those requiring specific treatment.

Several specific topics have emerged from our study. The symbolic language of Chemistry needs some additional explanation at the Greek secondary education curricullum as indicated by the Co for CO interchange and misunderstanding of the role of subatomic particles in constituting the atomic number and atomic mass respectively. It should also be made clear that although the vast majority of the classroom used solutions are aqueous, in general “solvent” does not correspond to “water”. Furthermore, care should be taken to emphasize the differences between homonyms like solvent, solute and solution, which is a continuous misconception.

Overall the achievements of students in small town high-schools appears to lie close to the average of the achievements of students in large city and rural area schools grouped together (Papadopoulos and Akrivos 2022). This is an indication that Greek students still perform as a uniform population, their scoring in demanding chemical tests varying smoothly and slightly with the transition from the more elite to the less esteemed schools.

The present study is by no means complete or conclusive. Further examination of results from different types of schools existing within the Greek secondary education should be collected and evaluated. In an additional step, a more detailed account of the degree of assimilation of stoicheiometry concepts may be achieved following an investigation of the results of students' long term memory. The project is underway with the construction and distribution of a third questionnaire targeting the same students during their senior high-school grade C studies.

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Note

Note 1. In the transfer of words between languages there would be applied a simplistic or an exact transcription of characters. It is common to refer to stoichiometry, an exact transfer from the Greek στοιχειομετρία, composed of two parts, στοιχείον (element) and μετρώ (to count). In our opinion the word should be transferred in English as either stichiometry, copying all the i-like sounds of Greek as simply “i” or stoicheiometry which seems more complicated although we adopt it here as an example of our point.