INTERPRETATION OF CHEMICAL REACTIONS ON SUB-MICRO LEVEL WITHOUT LABORATORY JARGON

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ABSTRACT

From experiences all over the world, we know that formulae and chemical equations are memorized very often or only equalized by counting the number of "atoms on the left and right side of the equation". Looking to our Chemical triangle (Fig. 1) lecturers and students are jumping from the Macro level just to the Symbolic level. If we would go first from Macro level to Sub-micro level and explain chemical reactions with involved atoms, ions and molecules, learners would understand chemistry more successfully. With a special questionnaire we are investigating the ability of university students and chemistry teachers in Indonesia and Tanzania to interpret given chemical equations with involved particles. We found a lot of misconceptions and proposed how to challenge them. Another problem may be the Laboratory jargon. Very often lecturers and teachers are mixing Macro and Sub-micro level, they read the well-known equation $2H_2 + O_2 \rightarrow 2H_2O$ with the words: "two hydrogens plus one oxygen form two water". Every expert knows that the molecules are meant, but the young learner asks: "grams or milliliters of those gases"? So please stay on the Macro level and read "hydrogen and oxygen react to water". Or take the Sub-micro level and read: "$2H_2$ molecules + $1O_2$ molecule react to $2H_2O$ molecules". Otherwise, misconceptions may arise, more examples can be found in the text. *[African Journal of Chemical Education—AJCE 13(2), June 2023]*

INTRODUCTION

There is a true story of the year 2003 at one of the Secondary schools at Kilimanjaro area in Tanzania. The teacher of a Form-VI class (highest level in schools) did a titration of hydrochloric acid, asked the students to interpret the change of indicator color – and soon the well-known equation was developed at the blackboard: $HCl + NaOH \rightarrow NaCl + H_2O$. Author BARKE interrupted the lesson with the question: “Please let me know which particles are reacting”. The teacher looked irritated and pointed out that „HCl and NaOH“ are involved. So BARKE went to the blackboard, sketched a beaker model and wrote inside „H^+(aq)“ and separated „Cl^-(aq)“. Suddenly a young girl came up with a beaker-model of NaOH solution: „Na^+(aq) and OH^-(aq)“. After some discussion about the function of sodium and chloride ions the students recognized that H^+(aq) ions and OH^-(aq) ions react to form H_2O molecules – other ions remain without reacting. The 50-years-old teacher came to BARKE and noticed: „Thanks for opening my eyes for interpreting neutralization. Why did you not come 30 years earlier – I would have explained neutralization every time like you have done it today”.

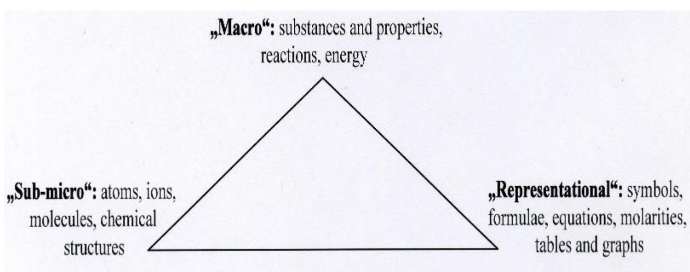

Fig. 1: JOHNSTONES Chemical triangle for Chemistry education [1]

This story shows that the Sub-micro level (see Fig.1) seems so important to understand neutralization in the scientific way. Also other acid-base and redox reactions are confusing learners if only full equations are stated: School-made misconceptions are coming up [2]. These reactions should be discussed and explained by reacting ions. Since 1928 BROENSTED proposed his idea to look not only to *substances* of chemical reactions but to involved *particles* which react [3]: for example, to H_3O^+(aq) ions which are proton donors and transfer protons to OH^-(aq) ions or other base particles.

In Chemistry teaching atoms and molecules as smallest particles of matter are well-known – but ions have been ignored in many curricula around the world: Misconceptions can be stated if particles in salt solutions or in mineral water are asked [2]. One example: If precipitation of barium sulfate from barium chloride and magnesium sulfate solutions should be described, one is mostly writing: „$BaCl_2 + MgSO_4 \rightarrow BaSO_4 + MgCl_2$".

But there are misconceptions of „partner change" and some curricula tell the precipitation as „double replacement reaction" [4]: „Barium and magnesium are changing partners". Taking the involved ions into account it is easy to write: $Ba^{2+}(aq) + SO_4^{2-}(aq) \rightarrow BaSO_4(s)$.

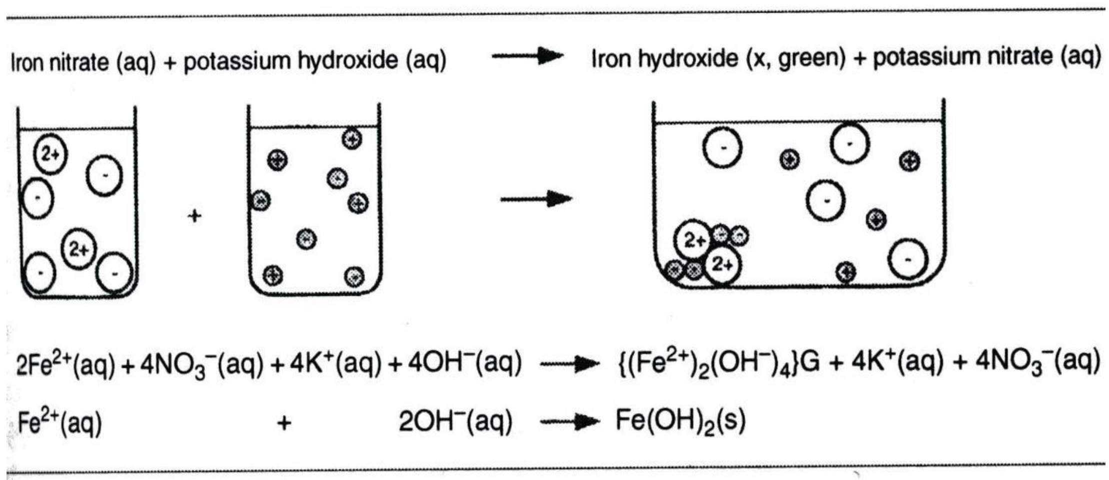

Fig. 2: Beaker model of iron (II)-hydroxide precipitation by salt solutions [5]

These ions are joining to form a $Ba^{2+}SO_4^{2-}$-ionic lattice, the other Mg^{2+}(aq) and NO_3^-(aq) ions are „spectator ions" in the sense of not reacting particles: those ions *remain*. The best way is to draw a concrete model of a precipitation (Fig. 2) and discuss this beaker model with the aim to develop a scientific mental model on the Sub-micro level [5]. We will investigate those abilities of students in higher semesters of several universities.

EMPIRICAL RESEARCH ACCORDING TO THE SUB-MICRO LEVEL

ASIH WISUDAWATI [6] developed a questionnaire to give university students the usual chemical equation of acid-base and redox reactions and asked questions according to the involved atoms, ions or molecules, also according to particles which do not react, according to the decision if there is an acid-base or redox reaction and the connected transfer of protons or electrons (see one example in the appendix).

At Indonesian universities of Yogjakarta and Bandung she applied the 10-tasks questionnaire (see appendix) and tested objectivity, reliability and validity successfully. During 60-minutes period students should solve the tasks, and about 75 answer sheets have been received. She got the following results [6]:

- Most of the tasks 2, 5 and 6 are answered in a right way and interpreted as redox reactions. But not in all cases students could mark those particles which are giving electrons, and particles which are taking electrons.
- Reactions 1, 3, 4 and 7 are interpreted in a right way as acid-base reactions – but nearly no student can mark particles which give protons or take protons. Acid-base reaction in task 8 gives problems: it is interpreted as redox reaction without explaining the decision. The weak acid "HAc molecule" is mostly seen as completely protolyzed into ions without explaining weak acids by equilibria between molecules and ions.
- Solid salts are often described without ions: "Na_2CO_3, $CaCO_3$ and MgO molecules" exist in the mind of students. So according to the question which particles are not reacting, metal ions composing all salt crystals are mostly not mentioned.

- **Question 9** asks about the most difficult alternative out of (a) – (d). Students are deciding mostly (d) according to the transfer of protons or electrons with following comments: „Proton or electron transfer confuses me; I need basic concepts of chemistry; we need to understand (a) – (c) for an answer; we need a lot of theory and more time to answer". Also (c) about "spectator ions" is confusing a lot of university students.
- **Question 10** concerns student's wishes for going deep into the Submicro level or not. Students answers: „yes – because it is important to learn what particles are doing; to differentiate acid-base and redox reactions better; it helps to understand chemistry; it can support to be a better teacher; I can improve my understanding of chemistry".

Just the last answers may give us an impression how much students will appreciate to get more information about atoms, ions and molecules which are involved in chemical reactions. As soon as learners interpret reactions on the Submicro level successfully, they understand the Chemistry behind – and chemical equations must not be memorized, they may be used as short information connected to mental models of those reacting atoms, ions and molecules. Especially the decision wheather an acid-base or a redox reaction occur and which particle donates or takes a proton or an electron can be completely understood.

BARKE gave in September 2018 same questionnaire to 20 experienced teachers during a one-week-teacher-training seminar in Moshi, Tanzania. The results are very different: some teachers answered nearly perfect, the majority has big problems [6]:

- Teachers cannot avoid the mixture of particles and substances: „H^+ ions and OH^- ions form *water*, H^+ ions and CO_3^{2-} ions form *water* and *carbon dioxide gas*". But we have this problem around the world: particles and substances are mixed (see later „Laboratory jargon").
- They also interpret reactions with „salt molecules", and if they want to show chemical structures of compounds they cut formulae into not existing ions: „$2H^+O^{2-}$, $Na^+O^{2-}H^+$, $2H^+S^{6+}O^{2-}$ " are some examples. Especially with combined ions like sulfate, nitrate or carbonate ions there are difficulties with indizes and exponents in formulae.
- Redox reactions and the equivalence of electrical charges on both sides of equations are other difficulties. Concerning reactions of iron and copper chloride solution Fe and Cu atoms are ignored: „$Fe^{2+} + Cu^{2+}Cl^- \rightarrow Fe^{2+}2Cl^- + Cu^{2+}$". Charges are also misunderstood and wrong calculated: „$Cu^{2+} - 2e \rightarrow Cu$ or $2\ Ag^+ \rightarrow Ag + 2e$ or $Zn + 2e \rightarrow Zn^{2+}$ " are examples.
- Acid-base reactions have been explained by „electron transfer" because teachers don't know proton transfers (this idea was given through the seminar): „$2\ H^+ + 2\ OH^- \rightarrow 2\ H_2O + 2e$ or $2\ H^+$ gain 2 e, OH^- looses 2e or H^+ is reduced, and OH^- is oxidized" are misconceptions.

Later after the seminar another a posttest has been performed – and the teachers could show their new knowledge concerning acid-base reactions with proton transfer, and redox reactions with electron transfer. So, we have to admit that teacher education in science and especially in Chemistry is very poor around many parts of the world because lecturers at teacher colleges mostly are not used to interpret those reactions on the Submicro level.

- Asking **task 9** about the difficulties according to (a) – (d) all four alternatives have been irritating the teachers because they have never answered those questions – and have not really understood differences in acid-base and redox reactions. At the end of the seminar they were very thankful to get new insights in the seminar and are now more sure how to explain those reactions scientifically, how to move successfully on the Sub-micro level.
- Even at the begin of the seminar teachers have grabbed the big meaning of the Sub-micro level and answered according **task 10** that they want to go deep into the Sub-micro level: „Indeed – there is much knowledge in this topic which is very important for teaching, on this way we want to understand more Chemistry“, have been some comments.

LABORATORY JARGON AND MISCONCEPTIONS OF STUDENTS

According to the Sub-micro level we have in chemistry another problem. Lecturers mostly use a "laboratory jargon" during their lessons and the question comes up whether teacher students take this jargon for their terminology, or even develop „school-made misconceptions" [2]. If they transfer them later as teachers to their students at schools, those misconceptions are going on and on. One example: "2 hydrogen react with 1 oxygen to form 2 water" is often stated by experts (and experts know that the involved molecules are meant). But students look to substances and may ask: "2g or 2 mL of hydrogen are involved?" As soon as they hear the scientific interpretation "2 H_2 molecules and 1 O_2 molecule are forming 2 H_2O molecules", they understand Chemistry - this last statement is totally clear and should be used.

JOLINE BUECHTER [6]. A German empirical pilot study has shown first results: About half of the investigated participants at University of Muenster could reflect and correct given jargon statements – but even after three years of studying chemistry the other students are staying with that jargon or other alternative conceptions. One example of the questionnaire where students have to mark the scientifically correct answer:

"2) Lab. Jargon: "Hydrochloric acid gives off a proton"

a) Hydrochloric acid can be deprotonated.

b) Hydrochloric acid can also absorb protons.

c) H_3O^+(aq) ions are present in hydrochloric acid, they can emit protons.

d) HCl molecules are present in hydrochloric acid, they release protons" [6].

The right answer is of course (c): "H_3O^+(aq) ions are present in hydrochloric acid, they can emit protons". BUECHTER took the famous misconception (d) and was waiting of "HCl molecules in solution". Because of the well-known idea of "deprotonation" we offered alternative (a), answer (b) is a fake [6]. The right answer (c) is chosen by 40 % of participants, the real misconception about "HCl molecules in hydrochloric acid" is fortunately taken by only 5 %. But answer (a) has reached the majority of 55 %: Many students are thinking of a scientifically sound of deprotonation. The questionnaire may be studied by BUECHTER [7].

Question	Germany	Indonesia	
1	68	92	84
2	40	15	19
3	90	54	50
4	77	63	59
5	55	48	45
6	22	25	33
7	50	15	22
8	82	83	65
9	64	79	87
10	55	23	31
	Year 3	Year 3	Year 1-4

YULI RAHMAWATI [6]. She created the English version of the questionnaire and took it to students of UNJ University of Jakarta/Indonesia. Similar results have been obtained (see Table). In question 2 Indonesian students took mostly answer (d) "Proton donor HCl".

In question 7 "Neutralization" many students decided "salt formation" as right answer – and not the reaction of H^+(aq) ions and OH^-(aq) ions. Related to question 10 "Amphoteric H_2O molecule" most students don't look to the H_2O molecule as proton donor and acceptor, but chose the substance: "water can be an acid or a base".

In Indonesia most explanations are given on base of substances – like problems experienced in Tanzania and Ethiopia – curricula should be improved to instruct also the Sub-micro level for understanding Chemistry.

CHALLENGE OF MISCONCEPTIONS

What shell we do to avoid those mentioned misconceptions with ions as important particles? As soon as atoms are well-known and metal atoms in metal structures are visualized by densest sphere packings, molecules should be introduced by ball-stick models and their molecular structural symbols. Also, the ions, the third group of smallest particles, should be introduced by their symbols and by models of the ionic lattice of salt crystals.

Usually, during the introduction of atoms the Periodic table is shown with all atomic symbols, numbers, and masses. If one takes spheres to visualize that every atom has a specific diameter, it is easy to also symbolize the corresponding ions with their specific diameter (see Fig. 3): Charge numbers are given without comparing any protons in the nucleus and electrons in the shell – the ions can be introduced without the differentiated atomic model! Later during higher classes students may work with the nucleus-shell model of atoms and ions and their number of electrons can be discussed for explaining ion charges.

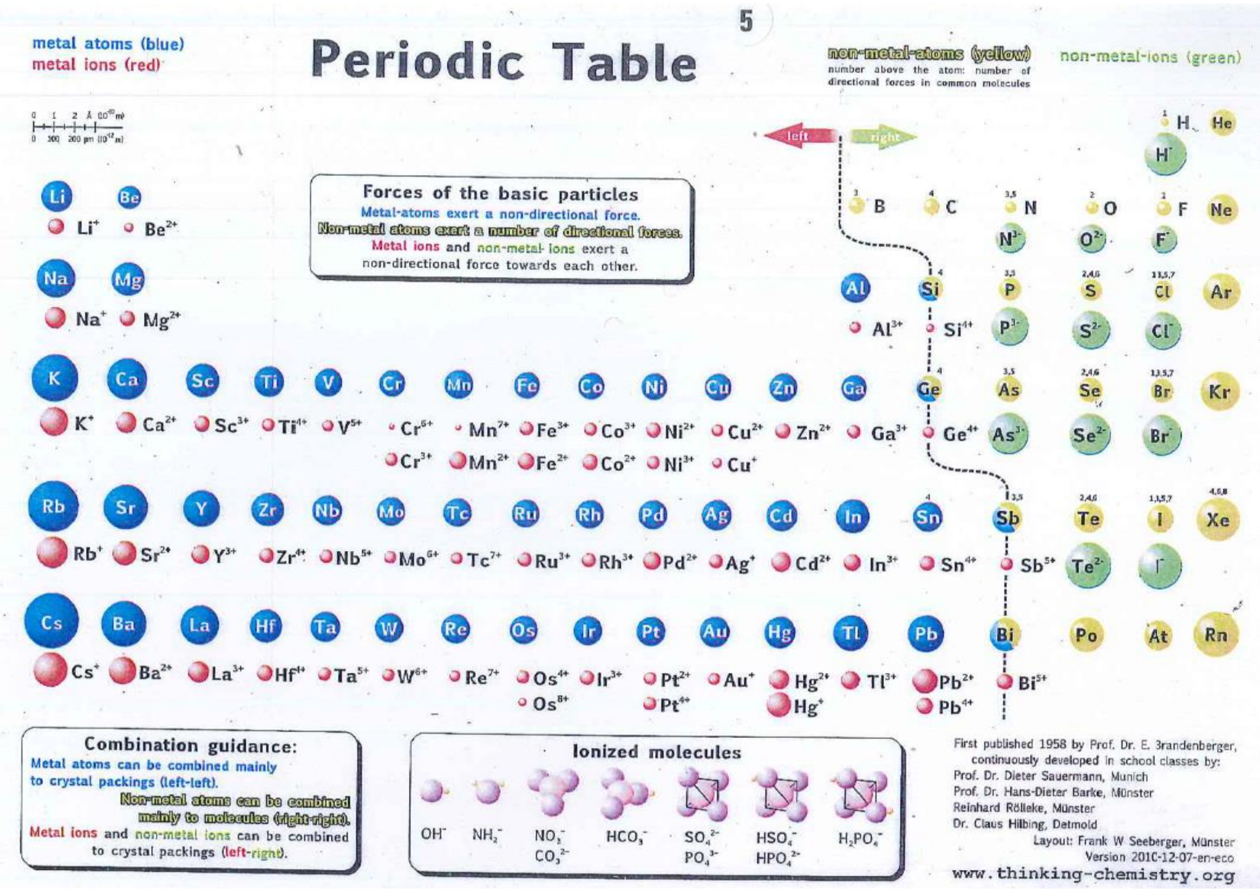

Fig. 3: PSE-depiction of a selection of atoms and ions and their spherical models [8]

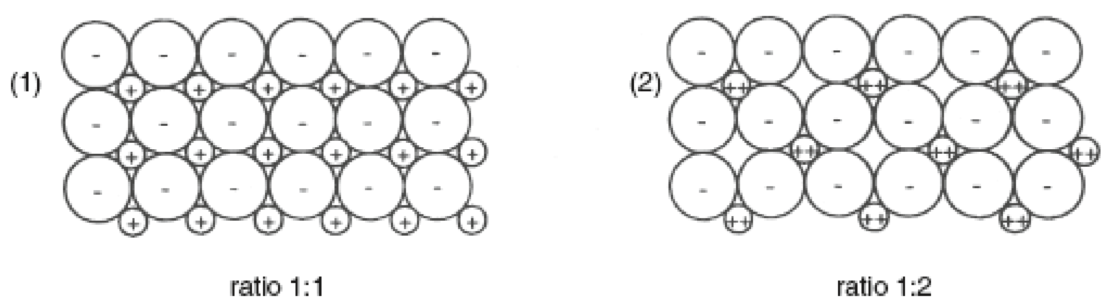

Fig. 4: 2-D models of ionic lattices in the ion ratio 1 : 1 (NaCl) and 1 : 2 ($MgCl_2$) [5]

Analogically to the composition of a water molecule by two H atoms and one O atom, one may state that sodium chloride is not composed of molecules, but of Na^+ ions and Cl^- ions in an ionic giant structure (Fig. 4, left side). If possible, a 3D-sphere packing of two different kinds of colored spheres should be offered or even built by students themselves [5] and discussed according to the 2D-model. By questions about the forces which hold the ions together, the idea of ionic bonding can be given: Ions with same charge are repelling, but ions with different charges are attracting – last forces are much higher and bind all ions in an ionic lattice. One can even discuss the melting temperatures of different salts: Sodium chloride melts by 800 ^oC, Magnesium oxide with same ionic lattice structure by 2850 ^oC.

In every case the ionic symbol for sodium chloride should be shown as $(Na^+)_1(Cl^-)_1$ or Na^+Cl^-. If only the NaCl symbol is used, the misconception according "NaCl molecules" may come up. The same will be repeated and reflected for magnesium chloride: $(Mg^{2+})_1(Cl^-)_2$ and the 2D-model (Fig. 4, right side). On this way students have chances to know that ions are composing those salts – and may avoid misconceptions of "salt molecules" [2]. After discussing the meaning of symbols those ionic formulae can be shorten to NaCl and $MgCl_2$ – but the involved ions should be in the mind of learners, in their mental model!

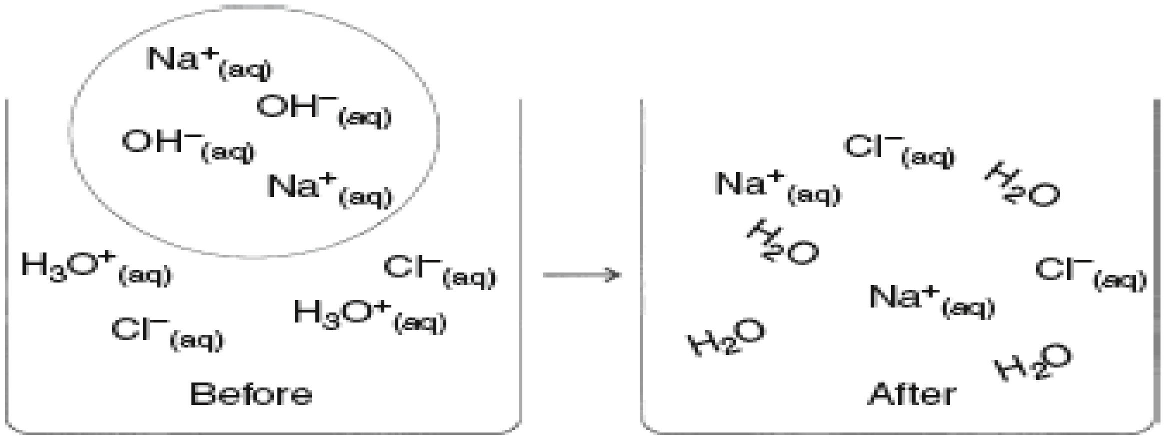

Fig. 5: Beaker model for neutralization of hydrochloric acid by sodium hydroxide solution [5]

If salt solutions will be introduced, (aq)-symbols should be added: Na^+(aq) ions and Cl^-(aq) ions for sodium chloride solution, Mg^{2+}(aq) and Cl^-(aq) ions in the ratio 1 : 2 for magnesium chloride solution. Those ratios can be visualized by beaker models to show that the ions are not organized by ion pairs but move separated from another in solutions (Fig. 2).

Students know the common equation for neutralization, in case of hydrochloric acid and sodium hydroxide solution: HCl + NaOH → NaCl + H_2O. Asking about the particles which are reacting often HCl and NaOH molecules are mentioned. So it is important to point out that H^+(aq) ions and OH^-(aq) ions are reacting, or in sense of BROENSTED [3] better an H_3O^+(aq) ion gives a proton to an OH^-(aq) ion:

H_3O^+(aq) ion + OH^-(aq) ion → 2 H_2O molecules

Even the neutralization of acids and bases should be reflected by beaker models (Fig. 5). The (aq)-symbol is important because the learner knows that different charged ions are attracting and may join together. The (aq)-symbols show hydrated ions: 4, 5 or 6 H_2O molecules are connected to every ion – avoiding the strong attraction of ions like in solid or molten salts.

It is also possible to open the discussion by a Concept cartoon (Fig. 6): Students can show their explanation out of four given answers, or can explain other conceptions – teachers know how students are thinking. The discussion may go in the direction of the boy on the right side: "After the reaction there are Na^+(aq) ions, Cl^-(aq) ions, and H_2O molecules".

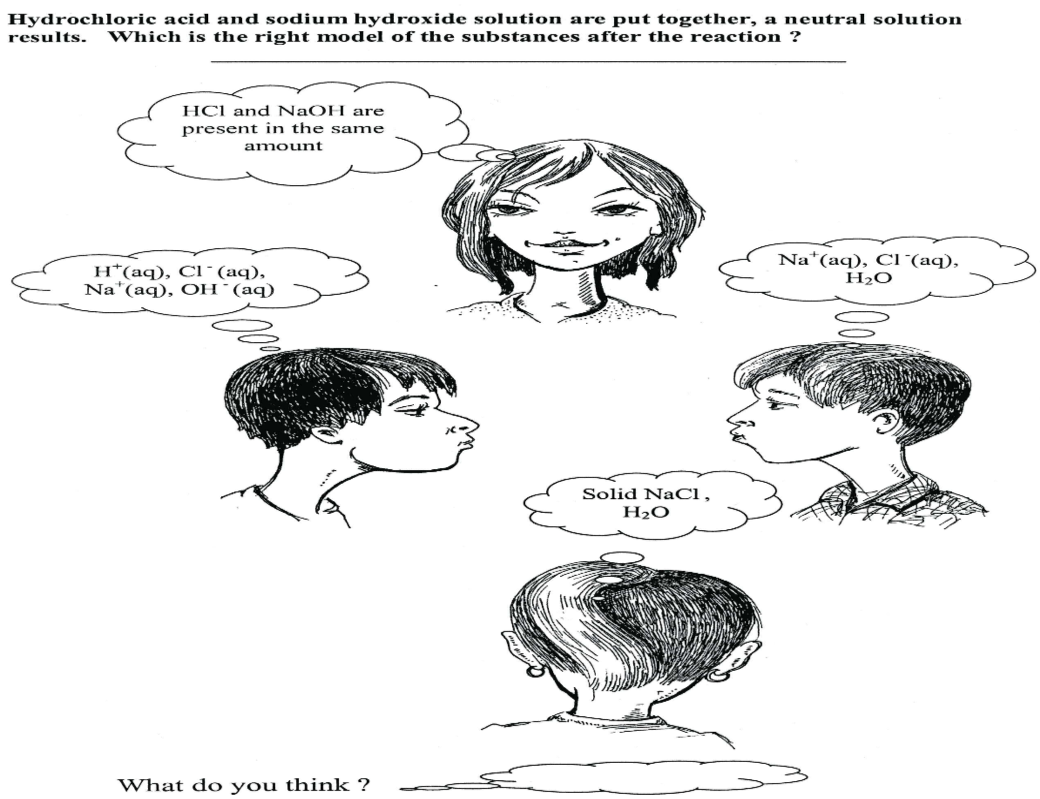

Fig. 6: Concept cartoon concerning neutralization reactions [9]

If acids like nitric acid or sulfuric acid are involved, the special Periodic Table (Fig. 3) shows also "combined ions" or "ionized molecules" like OH^-, NO_3^-, HCO_3^-, CO_3^{2-}, SO_4^{2-} and PO_4^{3-}. By this information students can even derive formulae of most acids, and salts like hydroxides, nitrates, carbonates, sulfates or phosphates: Na^+OH^-, $Mg^{2+}(NO_3^-)_2$, $Ca^{2+}CO_3^{2-}$, $(Na^+)_2SO_4^{2-}$ or $(K^+)_3PO_4^{3-}$. It seems important that students know composition and charge of those combined ions because they may separate formulae incorrectly into single ions – another misconception!

CONCLUSION

Chemistry is not easy to understand – if for example only full chemical equations are offered by lecturers even students at universities develop misconceptions. To challenge those misconceptions our curricula, have to extend chemical interpretation on the Sub-micro level. In chemical reactions involved atoms, ions and molecules should be discussed, especially to differentiate acid-base and redox reactions for answering successfully the question: “Which particle is giving protons or electrons, which particle is taking protons or electrons”?

Concerning the work with ions, ionic formulae of acids, bases and salts should be included into lectures. With help of the special Periodic system of atoms and ions (Fig. 3) one should combine the involved ions to ionic formulae, to models of salt crystals and ionic-lattice models (Fig. 4). One should also draw beaker models for visualizing solutions of acids, bases and salts (Fig. 2, 5). Students should develop accurate mental models – so misconceptions may be challenged.

One way to get information about misconceptions of students, special Concept cartoons [9] can be offered (Fig. 6). These cartoons contain the most well-known misconceptions in form of statements of students – only one answer is the scientific right one. In the shown example the boy on the right side

(Fig. 6) comes up with the correct answer: "Na^+(aq) ions, Cl^-(aq) ions, H_2O molecules". After diagnosing most mentioned misconceptions by the Concept cartoon in class the instruction can be planned accordingly – and after instruction the Concept cartoon can be applied another time to see if the scientific interpretation has reached most students. By this way students will understand Chemistry – and are even motivated to learn more!

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APPENDIX: Asih W. Wisudawati June 2018

Questionnaire "Redox or Acid-base reaction"?

For understanding Chemistry we need three levels of reflection:
1. **Macro level** of observations according to substances and chemical reactions,
2. **Submicro level** with interpretation of all observations with mental models by particles of matter like atoms, ions, molecules and by chemical structures,

3. **Symbolic level** with shortenings of mental models by chemical symbols like atomic, ionic, molecular symbols, and chemical equations. In following problems the macro and symbolic level is presented in this questionnaire, the submicro level is asked by participants.

One example for the wanted answers in the following eight problems:

Macro level: Magnesium reacts with hydrochloric acid, gaseous hydrogen is observed.

Symbolic level: $Mg(s) + 2\ HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$

Submicro level: **a) Which particles (atoms or ions or molecules) are involved?**

Answer: Mg atoms / H^+ ions, Cl^- ions / Mg^{2+} ions Cl^- ions (1:2) / H_2 molecules

b) Write down equation of those atoms, ions or molecules which react!

Mg atom + 2 H^+ ions $\rightarrow$ Mg^{2+} ion + H_2 molecule

c) Which atoms, ions or molecules are NOT reacting?

Cl^- ions are „spectator ions“

d) Redox or acid-base reaction? Explain transfer of electrons or protons.

Redox: Mg atom gives two electrons: Mg atom $\rightarrow$ Mg^{2+} ion + 2 e- (oxidation)

2 H^+ ions take two electrons: 2 H^+ ions + 2 e- $\rightarrow$ H_2 molecule (reduction)

Try to solve the next eight problems in this way!

Take a blank white paper and write down your answers according to (a) – (d).

1. Solid sodium carbonate reacts with hydrochloric acid, gaseous carbon dioxide is observed:
$Na_2CO_3(s) + 2\ HCl(aq) \rightarrow 2\ NaCl(aq) + H_2CO_3(aq)$ ($H_2CO_3 \rightarrow H_2O + CO_2$)

2. Zinc reacts with diluted sulfuric acid, gaseous hydrogen is observed:
$Zn(s) + H_2SO_4(aq) \rightarrow ZnSO_4(aq) + H_2(g)$

3. Acetic acid solution reacts with sodium hydroxide solution, small heat is observed:
$HAc(aq) + NaOH(aq) \rightarrow NaAc(aq) + H_2O$ (**H**Ac = **H**$OOCCH_3$)

4. Hydrochloric acid reacts with sodium hydroxide solution, big heat is observed:
HCl(aq) + NaOH)aq) $\rightarrow$ NaCl(aq) + H_2O

5. Iron reacts with blue copper chloride solution, brown copper develops on iron:
$Fe(s) + CuCl_2(aq) \rightarrow FeCl_2(aq) + Cu$

6. Copper reacts with silver nitrate solution, silver crystals are growing on copper:
$Cu(s) + 2\ AgNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + 2\ Ag$

7. Solid calcium carbonate reacts with acetic acid, gaseous carbon dioxide is observed:
$CaCO_3(s) + 2\ HAc(aq) \rightarrow CaAc_2(aq) + H_2CO_3(aq)$ ($H_2CO_3(aq) \rightarrow H_2O + CO_2$)

8. Solid magnesium oxide reacts with hydrochloric acid, magnesium oxide dissolves:
$MgO(s) + 2\ HCl(aq) \rightarrow MgCl_2(aq) + H_2O$

9. Let us know which of alternatives (a) – (d) was the most difficult for you. Explain.

10. Do you like to go with (a) – (d) so deep into the Submicro level? Explain.