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Proton Transfer: The First-Year Students' Conceptual Understanding

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Abstract

Modern Chemistry education shows acid-base reactions by proton transfer with regard to Bronsted's theory. Understanding how protons can be transferred by particles in solutions is quite challenging. The study aims to presents how university-first-year students are figuring out involved particles which take and give protons. Further, the enrolled participants in this study should explain how the process of proton transfer is running by selected particles but not by substances. Fifty-four students participated in this study that started from revealing participant's experiences on their previous education at senior high school. Subsequently, researchers conducted a pretest, learning planning, and learning implementation, finally a posttest. Qualitative analysis is preferred to analyze students' conceptions on particle level. The result shows us that there are two categories of participant's difficulties. First is determining the involved particles either all particles or reacting particles. The difficulties dominate on mixing terminology of atoms, ions, and molecules, also on preferences of memorizing and calculating oxidation state for chemical equations. The subsequent difficulty is the proton transfer process that caused by participant's failure on how they selected reacting particles. The systematic sequence on introducing and interpreting chemical equations has also presented as breakthrough.

Keywords: chemical equation understanding, first-year students, misconceptions, proton transfer

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1. Introduction

Students have difficulties interpreting chemical reactions and formulae by involved particles like atoms, ions, and molecules (Barke, 2009). The enormous task should be to do empirical research about those difficulties and questions: How should students learn the particle concept of matter in chemical reactions and how to interpret related formulae? These questions will lead teachers to teach not only the macroscopic level and formulae but also the essence of the sub-microscopic level in chemistry education.

In Johnstone's chemistry triangle, the sub-microscopic level in chemistry learning refers to students' mental model according to the idea of particle's nature. Surprisingly, teachers and learners normally directly move from the macro-level to the symbolic level through memorizing facts or rules (Kelly & Akaygun, 2016; Romine et al., 2016; Sutar et al., 2020) and counting the numbers of atoms on the left and right side of chemical equations (Barke et al., 2019). Accordingly, learners need to understand chemistry at the sub-microscopic level to avoid memorizing chemical formulas and equations without knowing the meaning.

To have a properly scientific understanding of acid-base reactions, learners should not only memorize facts, definitions, or algorithms in stoichiometry (Ortiz et al., 2012). They should also not only conduct chemical experiments in the laboratory. Learners, however, should try to understand the sub-microscopic chemical structures to equip themselves with adequate chemical knowledge.

Previous research on Indonesian grade 12 students found that the students could present the chemical reactions formula, but they could not describe the reaction at the particulate level (Agung & Schwartz, 2007). Research for interpreting chemical formulas is rare in Indonesia. Moreover, Indonesian students possessed misconceptions about the connected topic in this study, such as in covalent bonding concept (Erman, 2017). A study shows that the ability to represent a chemical reaction at the symbolic level does not guarantee the ability to predict the reactions at the particulate level (Kern et al., 2010). This finding leads to the question of to what extent university students in Indonesia can interpret chemical equations on the sub-microscopic level. This question is necessary to investigate because some studies revealed some misconceptions about the fundamental concepts of chemical reactions among Indonesian students (Maratusholihah et al., 2017; Prodjosantoso et al., 2019).

The existence of ions in solid salts and salt solutions is not commonly written through ionic symbols like Na^+Cl^- or $Ca^{2+}(Cl^-)_2$ for salt crystals, and $Na^+(aq) + Cl^-(aq)$ for aqueous salt solution. Therefore, electric conductivity of solutions can be used to indicate the presence of ions and/or molecules (Huheey et al., 2009; Kelly & Akaygun, 2016) and also from graphs of Microcomputer-Based Laboratory MBL (Ye et al., 2019). However, the existence of ions and/or molecules in solutions is not commonly written in chemical equations. Therefore, students will find it challenging to identify the particle level in chemical changes, and then they will develop complete mental models on the sub-microscopic level. The latest research has reported a lack of mental models in students' understanding of the interpretation of chemical equations (Schwedler & Kaldewey, 2020).

Another problem in the acid base concept is memorizing or recalling Arrhenius' theory to solve acid base problems. Arrhenius' theory is nonetheless correct according to scientific methodology. Still, this theory has limitations and cannot be applied at the sub-microscopic level since this theory belongs to the matter view (Kim et al., 2019). Shifting to modern acid-base concepts of Bronsted-Lowry is initially proposed to establish the function of particles. However, students mostly perceive Bronsted-Lowry's acid-base reactions model by memorizing the definition instead of applying examples. Besides that, students associate Arrhenius's definition with the existence of H^+ ions in solutions and with chemical equations like $HCl \rightarrow H^+ + Cl^-$ or $NaOH \rightarrow Na^+ + OH^-$. But one must point out that HCl molecules dissolved in water are meant for the first reaction, while Na^+OH^- ionic structures are for the second equation. Ions should be identified aside from existing atoms and molecules, and beaker models need to be introduced as well (see Figure 1).

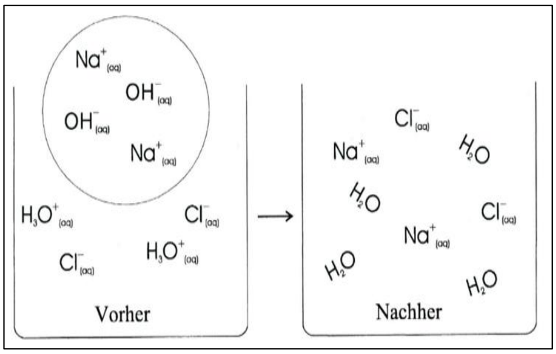


Figure 1. Beaker Models for Neutralization on The Sub-Microscopic Level (Barke & Buechter, 2018)

Subsequently, the research questions that want to be addressed in this study are how the first-year students figuring out the involved particle which give or take proton and how the first-year students explain proton transfer process based on their selected particle.

This study is essential correspond to several studies shows misconceptions patterns in which the participants tended to memorize the formula to determine the reaction type (Cokelez, 2010; Romine et al., 2016; Sutar et al., 2020). Consequently, we might find other misconception sources that will be discussed in this study as well.

2. Research Method

This study is part of preliminary actions for preparing the appropriate learning materials in general chemistry course for chemical education undergraduate university students. This research is quite qualitative descriptive showing the chunk of student's perceptions. Additionally, the first author conducted the two assessment methods (pretest & posttest) but without comparation through statistical calculation for obtaining the distinction of participants' conceptions. The main reason was to acknowledge the participants' conceptual ideas considering how they process the information based on the multimedia theory by Mayer. The information processing in the students' minds is associated with three assumptions of the cognitive theory of multimedia learning: dual channels, limited capacity, and active processing (Mayer, 2012).

Pretest: Consequently, for gaining perceptions on the chemical terminology online pretest was offered. Regarding the pretest, researcher asked participants to distinguish macro, micro, or symbol representations in Johnstone chemical triangle (Johnstone, 2006) by the following words and symbols: 1) Magnesium; 2) Mg; 3) Mg^{2+} ions; 4) $Mg(OH)_2$; 5) Magnesium oxide; 6) H_2O molecules; 7) Water; 8) is H^+ same with H_3O^+?; 9) is HCl (g) different with HCl (aq)?; 10) is HCl (aq) similar to $H_3O^+(aq)$ and $Cl^-(aq)$ ions?

Posttest: Researchers therefore applied again this instrument in the posttest. The validity and reliability of instrument had been evaluated during her research in Germany together with the second author. The questionnaire contains five number of chemical equations according to acid base reactions for submicroscopic interpretation. The time to answer was around 30 minutes. The following chemical equations are used to evaluate the participants' ability to figuring out the proton transfer concept:

1) $Na_2CO_3\ (s) + 2HCl\ (aq) \rightarrow NaCl\ (aq) + H_2CO_3\ (aq)$
   $(H_2CO_3\ (aq) \rightarrow H_2O + CO_2)$
2) $CH_3COOH\ (aq) + NaOH\ (aq) \rightarrow CH_3COONa\ (aq) + H_2O$
3) $HCl\ (aq) + NaOH\ (aq) \rightarrow NaCl\ (aq) + H_2O$
4) $CaCO_3\ (s) + 2CH_3COOH\ (aq) \rightarrow CH_3COOCa\ (aq) + H_2CO_3\ (aq)$
   $(H_2CO_3\ (aq) \rightarrow H_2O + CO_2)$
5) $MgO\ (s) + 2HCl \rightarrow MgCl_2\ (aq) + H_2O$

Further, the following question is provided for each chemical equation: a) Which particles (atoms or ions or molecules) are involved?; b) Write down the equation of those atoms, ions, or molecules which react!; c) Which atoms, ions, or molecules are NOT reacting in the reaction?; d) Redox or acid-base reaction? Explain the transfer of electrons or protons.

2.1. The Participants

The fifty-four university first-years students often got their preconception about basic chemistry since their studies in senior high school. Poorly, the participants in this study only gained basic chemistry through online learning since the covid pandemic. The enrolled participants are students in academic years 2022/2023. We want to evaluate their preconception about their particle concept according to acid base reactions.

2.2. Data Collection and Analysis

Currently, the research is still running for the next stage. Yet, in this article we want to share our initial finding as significant consideration for the next stage of research. Corresponding to our first report, we conducted five methods (see Figure 2).

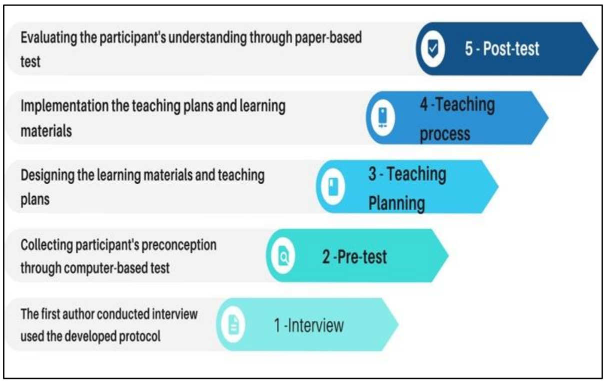


Figure 2. The Research Sequences

The first sequence of research are interviews and pretest for gaining their chemistry knowledge according to Johnstone chemical triangle. Afterwards, teaching plans and learning materials should be done based on the initial interview. The last part was to conduct the posttest examining through the questionnaire. In term of learning process, researcher implied Johnstone's three chemical representations at the same time. In this stage, the first author did her teaching for more than ten times. After that, the first author took the assessment with the valid and reliable instruments that had been developed with the second author. Those all-research process have been realized at August-October 2022.

Students' results were therefore analyzed by first author and sent to second author. Further, both of authors reviewed the manuscript to be publishable. Analyzing those results, we got two big problems: how the participants are able to understand all involved particle from the given chemical equations and how they identify particle which give proton or take proton.

3. Result and Discussion

We would like to start from the participant background of chemistry learning experiences. Almost all of them obtained the limited chemistry learning during their time in school. The main reason was covid pandemic that forced them to do online learning with its disadvantages and challenge. Based on this background, researchers tried to obtain their perception that related to chemical terminology.

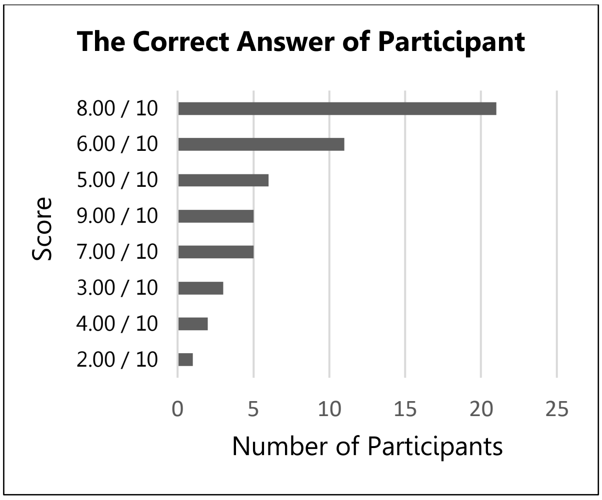


Figure 3. Graph of Correct Answers of Participants in The Terminology Pretest

Figure 3 shows us that participants found it hard to use scientific terminology: when the name magnesium is called, magnesium metal is meant in the macroscopic representation, every portion containing millions of Mg atoms. On the submicroscopic representation the symbol Mg means one Mg atom.

Corresponding to terminology pretest, the most difficult task is how they figure out that acidic solution contains H^+ ions or H_3O^+ called hydronium ion because the H^+ ions or proton does not exist by itself but rather as a hydrated hydrogen ion. This concept is important to lead participants to think on the submicroscopic level.

Another lowest score in the pretest was number nine and ten. Here, participants were confused on distinguishing between HCl(g) and HCl(aq), they could not answer the question number ten related to the ions in hydrochloric acid solution.

The significant causes are analyzed: participants hold difficulties on the sub-microscopic level for distinguishing between HCl(g) and HCl(aq). Scientifically, hydrochloric acid solution contains H^+ ions and Cl^- ions surrounded by six H_2O molecules that we are used to call hydrated ions (Barke et al., 2018). It is compared to hydrogen chloride contain one molecule HCl(g) that when we have 1 mol HCl(g) will contain $6{,}02 \times 10^{23}$ HCl molecules. Figure 4 might help the participants understand on sub-microscopic level.

The following is participants' misconceptions that significant to address the research questions mentioned above.

3.1. Involved Particle Which Gives or Takes Proton

Arrhenius' acid-base concept has a limitation to the solution in water (Chang & Goldsby, 2014). There are two things found in examining bond-breaking and bond-forming for simple hydrogen and hydroxide ions. First, reactions can be interpreted as transferring a proton (hydrogen ion) from acid molecules to hydroxide ions. Second, hydroxide ions cannot receive only protons, but other particles also receive protons like NH_3 molecules (Peters, 1990; Wilson & Newall, 1968). This observation was announced independently by Johannes N. Bronsted and Thomas M. Lowry in 1923. Acids are particles that donate protons, while bases are defined as particles that accept protons (Drechsler & Schmidt, 2005).

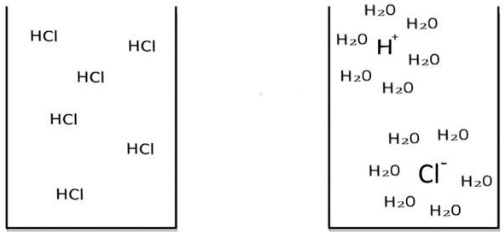


Figure 4. Beaker model for hydrogen chloride gas [HCl(g)] and hydrochloric acid [HCl(aq)]

Corresponding to participants' misconceptions, the initial difficulties emerged on particularly on understanding HCl(g) and HCl(aq) on sub-microscopic level. Figure 4 might could help student to differentiate between HCl(g) and HCl(aq) on the particle level. Students are expected to think that only HCl molecules will give protons to H_2O molecules. Further, regarding particle concept, symbol HCl(aq) should be meant as $H^+(aq)$ ions and $Cl^-(aq)$ ions which are hydrated by six H_2O molecules. Subsequently, as a teacher is expected to avoid writing the following eq.1, because HCl(aq) has already contained those mentioned ions above and no HCl molecules.

$$HCl(aq) + H_2O(l) \rightarrow H_3O^+(aq) + Cl^-(aq) \text{ (eq. 1)}$$

One of misconception prevention might through writing hydrochloric acid (aq) for solution and hydrogen chloride (aq) for the gas in Macro level. On the other hand, on sub-micro level, teachers might could introduce writing Hydrochloric acid solution with the ions like $H^+(aq)$ ions or $Cl^-(aq)$ ions where the ions are hydrated by a special number of H_2O molecules, mostly 6.

Related to the results, first-year students might be expected to distinguish which particle take or give proton. Proton-donor such as HCl(g) molecules release their proton (see eq. 2 and Figure 5). While the base is a proton-acceptor, such as $NH_3(g)$ molecules which pulls H^+ ions out from H_2O molecules (see the eq. 3 and Figure 6).

$$HCl(g) + H_2O(l) \rightarrow Cl^-(aq) + H_3O^+(aq) \text{ (eq. 2)}$$

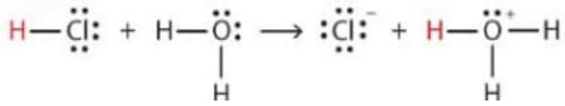


Figure 5. Mechanism of Proton Transfer Between HCl and H_2O Molecules

$$NH_3(g) + H_2O(l) \rightarrow NH_4^+(aq) + OH^-(aq) \text{ (eq. 3)}$$

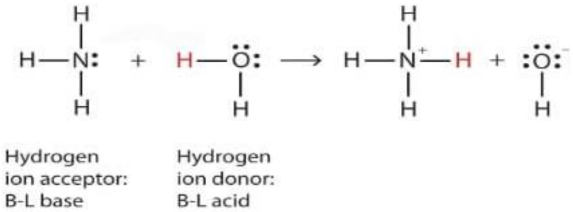
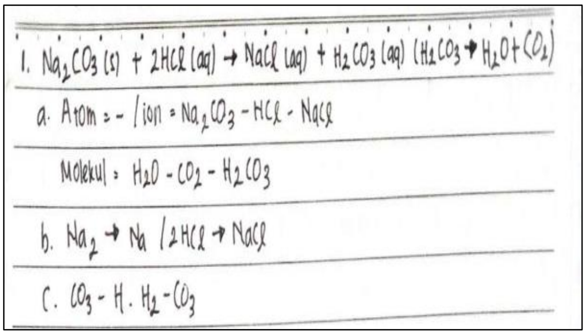


Figure 6. Mechanism of Proton Transfer Between NH_3 and H_2O Molecules

Both the chemical equations above show us which particles gives or takes proton: this is mandatory for understanding acid base reactions in the scientific way. Figure 5 show us that HCl molecules will give proton whereas H_2O molecules will give proton (Figure 6). In here, the electronegativity of atom and the pulled species will influence which molecules release its proton. More electronegative of atom that bond to hydrogen would easily release its proton and vice versa. Based on Figure 5 and 6, the electronegative atoms are O and N. Another influenced factor of proton transfer are atomic radii and conjugated bonding. In the basic understanding, we apply the net ionic reactions to reveal the involved particles in the solutions. Based on the data, the participants in this study show their difficulties on choosing all involved particles whether ions, atoms, or molecules and selecting those particles which react or not as shown as Figure 7.

Based on the two participants' answers of the questionnaire above (see Figure 7 and 8), we might suppose that participants hold lack of knowledge to identify particles in chemical equations whether containing ions or not. This skills on understanding ionic symbols are needed as requirement of understanding the sub-micro level. As such, Figure 7 shows us that their confusion on spelling atom or ion for symbols Na_2CO_3(s) and HCl(aq). In contrast, in Figure 8, they almost understand that HCl in solution would be protolyzed to become H^+ (read: H_3O^+) and Cl^- ions. While in the second question they suppose that those both ions become H_2 molecules and O_2 molecules. The appearance of misconceptions in term of particle reactions remain on participant's misunderstanding. Indeed, for acid base reactions with weak acid in the following answer still trigger misconceptions (Figure 9).



1. $Na_2CO_3 (s) + 2HCl (aq) \rightarrow NaCl (aq) + H_2CO_3 (aq)$ $(H_2CO_3 \rightarrow H_2O + CO_2)$

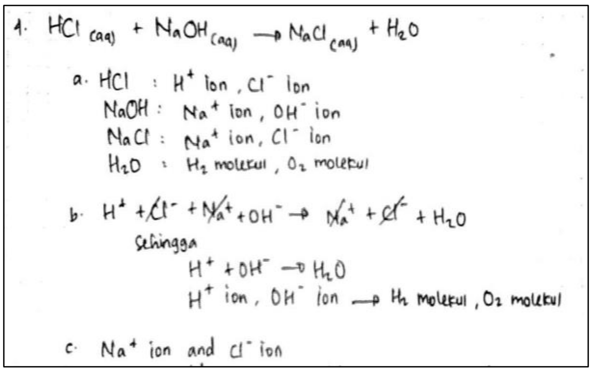
a. Atom : - / ion = Na_2CO_3 - HCl - NaCl

Molekul : H_2O - CO_2 - H_2CO_3

b. $Na_2 \rightarrow Na$ / $2HCl \rightarrow NaCl$

c. CO_3 - H . H_2-CO_3

Figure 7. The Participant's Answer for Solid Ionic Salt



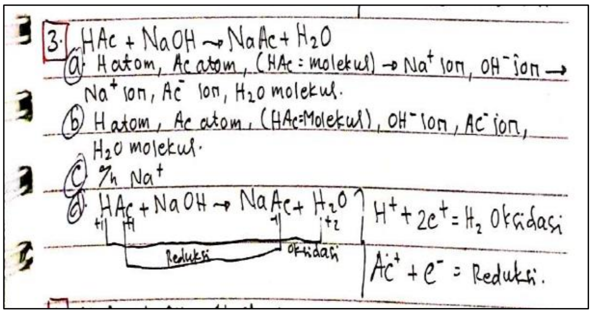
1. $HCl_{(aq)} + NaOH_{(aq)} \rightarrow NaCl_{(aq)} + H_2O$

a. HCl : H^+ ion , Cl^- ion
NaOH : Na^+ ion , OH^- ion
NaCl : Na^+ ion, Cl^- ion
H_2O : H_2 molekul , O_2 molekul

b. $H^+ + \cancel{Cl^-} + \cancel{Na^+} + OH^- \rightarrow \cancel{Na^+} + \cancel{Cl^-} + H_2O$
sehingga
$H^+ + OH^- \rightarrow H_2O$
H^+ ion , OH^- ion $\rightarrow$ H_2 molekul , O_2 molekul

c. Na^+ ion and Cl^- ion

Figure 8. Participants' Answer for Acid Base Compound



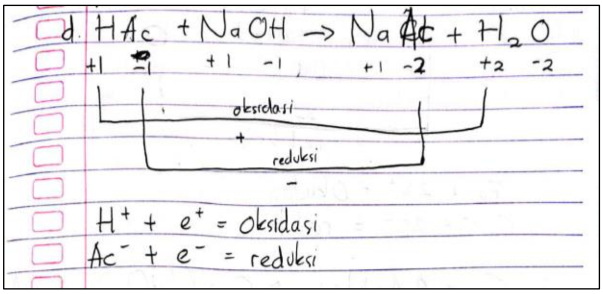
3. $HAc + NaOH \rightarrow NaAc + H_2O$
ⓐ H atom, Ac atom, (HAc : molekul) → Na^+ ion, OH^- ion → Na^+ ion, Ac^- ion, H_2O molekul.
ⓑ H atom, Ac atom, (HAc=Molekul), OH^- ion, Ac^- ion, H_2O molekul.
ⓒ % Na^+
ⓓ $\underset{+1}{H}\underset{-1}{Ac} + NaOH \rightarrow Na\underset{-1}{Ac} + \underset{+2}{H_2}O$
Reduksi
Oksidasi
$H^+ + 2e^+ = H_2$ Oksidasi
$Ac^+ + e^- =$ Reduksi.

Figure 9. The Weak Acid Problem

Consistency on determining reacting particles whether atoms, ions, or molecules is still challenging. As we can see in Figure 9, the participant explained that acetic acid or CH_3COOH (or HAc) is figured out as H atom and Ac atom apart from he/she also proposed HAc molecules. But, once we look to the result, he/she could explain NaAc containing Na^+ ions and Ac^- ions. By the second answer he/she thought that particles are changing from Ac atom to become Ac^- ion. It is odd style of participant's' answers in determining which particles react and which not. Without thinking successfully on sub-microscopic level, several misconceptions will appear.

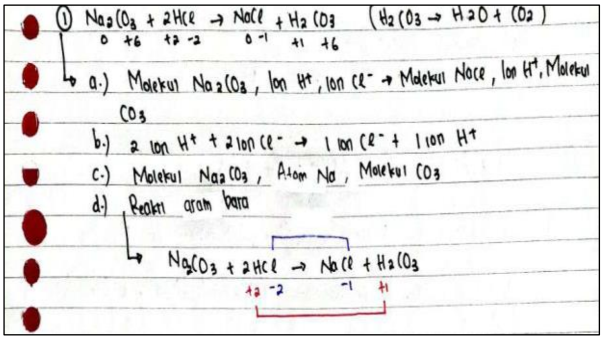
3.2. Proton Transfer Process Based on Their Selected Particles

Thinking about the particle concept requires correct system thinking. System thinking is the ability to understand and interpret complex systems that engage visualization abilities for intercorrelation and relationships between parts in the system (Orgill et al., 2019). In this case, complex system is owed in chemical equations particularly for acid-base equations. We expected that participants can determine the proton (hydrogen ion/ H^+ ion) that is slipping to H_2O molecules becoming H_3O^+ ions or hydronium ions. These ions will transfer protons to other basic particles. Corresponding to the last sequence in term of determining all particles, reacting or not, difficulties for determining the proton transfer still appear. We can see with Figure 10 the trend of participant's preferences to choose the redox concept for explaining acid-base reactions.



d. $\underset{+1}{H}\underset{-1}{Ac} + \underset{+1}{Na}\underset{-1}{OH} \rightarrow \underset{+1}{Na}\underset{-2}{Ac} + \underset{+2}{H_2}\underset{-2}{O}$
oksidasi
+
reduksi
−
$H^+ + e^+ =$ oksidasi
$Ac^- + e^- =$ reduksi

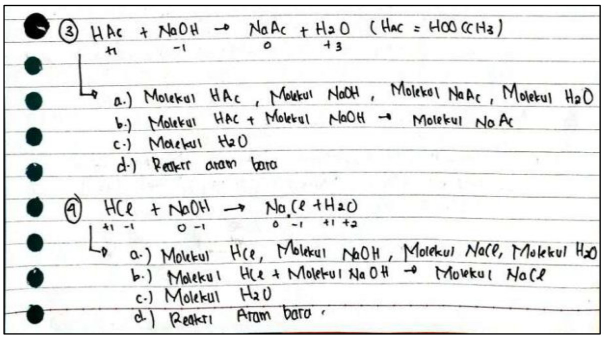
Figure 10. The Trends of How the Participant Decide the Mechanism of Proton Transfer



① $Na_2CO_3 + 2HCl \rightarrow NaCl + H_2CO_3$ ($H_2CO_3 \rightarrow H_2O + CO_2$)
0 +6 +2 -2 0 -1 +1 +6
a.) Molekul Na_2CO_3, Ion H^+, Ion Cl^- → Molekul NaCl, Ion H^+, Molekul CO_3
b.) 2 Ion H^+ + 2 Ion Cl^- → 1 Ion Cl^- + 1 Ion H^+
c.) Molekul Na_2CO_3, Atom Na, Molekul CO_3
d.) Reaksi asam basa
$Na_2CO_3 + 2HCl \rightarrow NaCl + H_2CO_3$
+2 -2 -1 +1

Figure 11. The Participant's Thinking of Oxidation State on Acid Base Reaction

Corresponding to Figure 10 and 11, the appearance of oxidation state calculation for acid base reactions is significantly appealed students for explaining proton transfer. The participants tended to recall the oxidation state for chemical formulas. But this method is only sufficient for redox reactions.



③ $HAc + NaOH \rightarrow NaAc + H_2O$ ($HAc = HOOCCH_3$)
+1 -1 0 +3
a.) Molekul HAc, Molekul NaOH, Molekul NaAc, Molekul H_2O
b.) Molekul HAc + Molekul NaOH → Molekul NaAc
c.) Molekul H_2O
d.) Reaksi asam basa
④ $HCl + NaOH \rightarrow NaCl + H_2O$
+1 -1 0 -1 0 -1 +1 +2
a.) Molekul HCl, Molekul NaOH, Molekul NaCl, Molekul H_2O
b.) Molekul HCl + Molekul NaOH → Molekul NaCl
c.) Molekul H_2O
d.) Reaksi asam basa.

Figure 12. The Trend of Memorize of Type of Reaction

Additionally, the difficulties of explaining proton transfer result from thinking mostly of molecules than ions if solid salts are involved (Figure 12). This is similar to Nyachwaya's et al. (2014) study that participants memorize acid-base reactions that produce salts, carbon dioxide, and water. Here, understanding acid-base reaction symbolism is not possible because learners tend to memorize formulas and chemical equations frequently (Barke et al., 2019; Nyachwaya et al., 2014).

Correspond to the difficulties before, schoolbook authors or teacher should follow special sequences in the introduction of formulas and equations: 1) Explaining the macroscopic level of substances by trivial and IUPAC names; 2) Highlighting the function of phase symbols for substance names; 3) Starting the symbolic level, reminding for writing general formulas; 4) Clearly distinguishing particles on sub-microscopic level; 5) Paying attention to writing the correct stoichiometry in chemical equations; 6) Presenting the ionic formulas for ionic compounds, molecular formulas for molecules; 7) Discussing comparisons between general, molecular, and ionic formulas.

4. Conclusion

Two main challenges appear on understanding Bronsted-Lowry's proton transfer theory. First it is the challenge of determining all involved particles based on given chemical equations that connect to difficulties on understanding which particle react and which not. There are difficulties on explaining proton transfer mechanism based on the previous stages on identification of particles. The results showed the inclination of memorizing intrinsic chemical species and rules to solve the problem.

Source of the participant's difficulties are laid on three factors. First there is inconsistency of chemical terminology. Second is history of chemistry through mixing Arrhenius theory and Bronsted-Lowry theory. The last one is lack on writing net ionic equations concept.

Challenging those misconceptions by introductions of well-organized symbols. The sense of formula and chemical equations can be obtained by applying the didactical PSE (Periodic System of Elements). This PSE shows atoms and ions of many elements and visualizes them with spherical models relates their different size. By this way students gain first knowledge of the ion existence before they have detailed instruction according to the atomic model with nucleus and shell.

By this instruction students at universities and schools can obtain a particle-related view in Chemistry. If they get the knowledge concerning ionic lattices in solid salts and write the ionic symbols, they will develop scientific mental models. If they think on separated and hydrated ions in aqueous solutions and write ions with (aq)-symbols they may gain so much more understanding than with usual formulae. They will understand proton and electron transfer from particle to particle - and will develop a modern understanding of Chemistry.

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