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Broensted Acids and Bases: History, Misconception, and Application Today

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ABSTRACTS

The purpose of this study was to explain a short literature review on Broensted Acids and Bases. This study explains the history of this theory and what application today is available. This study will be important to give crucial information to students, educators, teachers, as well as researchers.

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1. INTRODUCTION

In chemistry education, we are discussing mainly two concepts of acids and bases, known as the theories of Arrhenius and Broensted. For the first theory, dissociation into ions is generally discussed. Specifically, it relates to acidic solutions that contain $H^+(aq)$ ions, and alkaline solutions that contain $OH^-(aq)$ ions. This theory, therefore, deals with substances, which are referred to as acids and bases. Or, it would be even better to take the logical names "acidic and alkaline solutions". If both solutions are mixed in equivalent quantities, the $H^+(aq)$ ions react with $OH^-(aq)$ ions to form H_2O molecules, while the other ions remain in solution (in exceptional cases an insoluble salt may precipitate: sulfuric acid solution reacts with barium chloride solution to solid white barium sulfate and water).

The Broensted theory defines proton transfers: a molecule or an ion transfers a proton to another molecule or ion, and two conjugated acid-base pairs are involved. Thus, Broensted acids and bases are no more substances, but individual types of particles. Due to the autoionization of H_2O molecules (not "autoionization of water"), the following equilibrium exists:

$$H_2O \quad + \quad H_2O \quad \leftrightarrows \quad H_3O^+(aq) \quad + \quad OH^-(aq)$$

Through this protolysis, it is more advantageous to argue rather with $H_3O^+(aq)$ ions than with $H^+(aq)$ ions. In this theory there are still ampholyte particles that react as acid or as base particles depending on the reaction partners: H_2O molecules, NH_3 molecules, HSO_4^- ions – water, ammonia, or sodium hydrogen sulfate cannot be regarded as ampholytes. The original publication of Broensted from 1927 makes clear that acids and bases should be molecules or ions, but not substances (Brönsted, 1928).

Based on previous studies (Hibling & Barke, 2000; Barke, 1993; Barke & Engida, 2001; Barke, 2012; Barke & Büchter, 2023), here, the purpose of this study was to explain a short literature review on Broensted Acids and Bases. This study explains the history of this theory and what application today is available. This study will be important to give crucial information to students, educators, teachers, as well as researchers.

2. METHODS

This study is a literature survey and review. All data were obtained from current knowledge and literature on the internet source as well as books and articles from international journals.

3. RESULTS AND DISCUSSION

3.1. Misconceptions among students

"Sulfuric acid releases 2 protons, phosphoric acid 3 protons", a candidate in the examination colloquium was sure with his assertion. When asked whether 1 mg or 1 mL of substance is meant, the candidate shakes his head and says after some time of meditation: "of course I mean the H_2SO_4 molecule and the H_3PO_4 molecule " – "so please say it next time this way", was my answer. We all know that there is laboratory jargon among chemists, and chemists may maintain this jargon. But in chemistry didactics and chemistry education we must offer successful learning of the scientific language: "the H_2SO_4 molecule can emit two protons".

In a written exam, students were asked to formulate basic facts according to the topic "acids and bases" before considering a lesson plan for this topic. Most of the students were not capable to write a free text without mistakes – they showed "school-made misconceptions".

They mostly mixed the levels of substances and particles. For the reaction of mineral tablets with water, they wrote: "carbonate ions are reacting with citric acid" – rather than referring either to the level of substances with the reaction of calcium carbonate and citric acid or to the level of small particles, with the reaction of carbonate ions and citric acid molecules. For neutralization they often quoted: „$HCl(aq) + NaOH(aq) \rightarrow Na^+(aq) + Cl^-(aq) + H_2O(aq)$" – and mentally mixed substances and ions in one equation.

Consequently, they should either describe the substances:

$$\text{hydrochloric acid(aq)} + \text{sodium hydroxide(aq)} \rightarrow \text{sodium chloride(aq)} + \text{water}$$

or, we can specify the ions of hydrochloric acid and sodium hydroxide in the equation:

$$H_3O^+(aq) + Cl^-(aq) + Na^+(aq) + OH^-(aq) \rightarrow Na^+(aq) + Cl^-(aq) + 2\ H_2O(aq)$$

or, we can rewrite

$$H_3O^+(aq)\ \text{ions} + OH^-(aq)\ \text{ions} \rightarrow H_2O\ \text{molecules}$$

or, we can make it shorten as

$$H_3O^+\,(aq) + OH^-\,(aq) \rightarrow 2\ H_2O\ (aq)$$

If the ions in such a reaction equations are not formulated, but only empirical formulae such as $HCl + NaOH \rightarrow NaCl + H_2O$, then students very often think of "HCl molecules, NaOH molecules, and NaCl molecules", and sometimes they describe those “molecules” with symbols like “H-Cl, Na-O-H or Na-Cl".

The “Arrhenius theory” is often mentioned, but instead of relating it adequately to dissociation, it is often incorrectly connected with proton transfer – vice versa, when talking about the “Broensted theory” of protolysis, students stay with the dissociation: "hydrochloric acid is dissociated into ions, strong acids dissociate completely in solution, acetic acid does not dissociate completely, weak acids are characterized by the ratio of dissociated and not-dissociated molecules". Thus, the terms of both theories are mixed without understanding the historical genesis of those theories.

Also, the term "ampholyte" by Broensted has often been used incorrectly: "water is an ampholyte, it can react both as an acid and as a base" (instead of the H_2O molecule to be labeled as an ampholyte), the "autoionization of water" is noticed (not the autoionization of H_2O molecules), "the concentration of the water” is calculated as 55 mol/L (rather than the concentration of 55 mol H_2O molecules per liter). Also, not applicable remarks such as "hydrochloric acid releases one proton, citric acid can deliver up to three protons" are very problematic: in hydrochloric acid, the H_3O^+ (aq) ion can release one proton, in citric acid the H_3Cit molecule a maximum of three protons. Sulfuric acid is didactically difficult to communicate: in pure sulfuric acid, H_2SO_4 molecules are the proton donors, in half-concentrated acid, the $HSO_4^-(aq)$ ions and $H_3O^+(aq)$ ions, in diluted sulfuric acid only the $H_3O^+(aq)$ ions – as in any diluted solution of strong acids.

For “neutralization” reactions, students tend to write "acid and base are in equilibrium" – as if there is no reaction and equivalent amounts exist coevally. It is also stated that "salt formation" is a criterion for neutralization reactions – instead of H_2O molecules being formed. If students quote that the result of the standard neutralization reaction is "$NaCl(aq) + H_2O$", they mostly are thinking of NaCl molecules”, sometimes of “Na-Cl molecules.

In the neutralization of acetic acid solution, the reaction of H_3O^+ (aq) ions is mostly foregrounded, while the reaction of acetic acid molecules (HAc) is ignored. Since the degree of protolysis is about 1%, HAc molecules and ions exist in a ratio of 99: 1 – so especially these molecules react by neutralization: $HAc(aq) + OH^-(aq) \rightarrow H_2O(aq) + Ac^-(aq)$.

The “strength of acids” is often described by the pH value: "weak acids have a pH of 3 and higher". It should be seen that each solution of a strong acid can be diluted to the "pH of 3 and above”: protolysis equilibrium and degree of protolysis are parameters for weak acids.

3.2. Historical considerations of Broensted’s theory

In his essay "On the theory of the acid-base function" [1] Broensted alluded already in the title to the *function* of acid and base molecules and left out the usual discussion of the properties of acidic and alkaline solutions. In particular, he identified the function through a central mental model:

$$\begin{array}{ccccc} A & \leftrightarrows & B & + & H^+ \\ \text{acid} & & \text{base} & + & \text{proton} \end{array}$$

By donating a proton, the acid reacts to a base: "The A and B molecules are called corresponding acids and bases. By this definition, the OH^- ion loses the special position of the bases: by losing a proton, any molecule A is transformed to a minus-charged base molecule". When HCl molecules react with NH_3 molecules, both molecules change into ions: NH_4^+ (corresponding acid) and Cl^- (corresponding base). Broensted also deals with "free H^+ ions" that do not exist in a solution. He, therefore, states: "an acid molecule A only releases a proton when the proton is simultaneously assimilated by a base molecule":

$$\begin{array}{ccccccc} A1 & + & B2 & \leftrightarrows & A2 & + & B1 \\ \text{acid1} & & \text{base2} & & \text{acid2} & & \text{base1} \end{array}$$

All these statements show that Broensted is discussing molecules and ions – not substances. Supposing that a free proton does not exist in the solution, the formulation of the hydronium ion H_3O^+ is following:

$$\begin{array}{ccccccc} A & + & H_2O & \leftrightarrows & B & + & H_3O^+ \\ \text{acid1} & & \text{base2} & & \text{base1} & & \text{acid2} \end{array}$$

He furthermore states: "Whenever a proton is transferred from an electrically neutral molecule to another electrically neutral molecule, two ions of opposite charge arise". So, if H_2SO_4 molecules react with H_2O molecules, three types of ions are created: H_3O^+ ions, HSO_4^- ions, and SO_4^{2-} ions. Concerning the neutralization reaction, Broensted showed a very modern view: “When hydrochloric acid ($H_3O^+ + Cl^-$) and sodium hydroxide ($Na^+ + OH^-$) are mixed in aqueous solution, the formation of the salt $Na^+ + Cl^-$ seems only a purely mechanical mixing process ...... the typical process of neutralization of strong acids and bases is thus not the salt formation. Instead, the actual acid-base reaction is:

$$\begin{array}{ccccccc} H_3O^+ & + & OH^- & \rightarrow & H_2O & + & H_2O \\ \text{acid1} & & \text{base2} & \rightarrow & \text{base1} & & \text{acid2”.} \end{array}$$

Already in 1927, Broensted emphasized the formation of water molecules while many curricula today still argue with the "salt formation" by neutralization. Broensted also consistently described the molecules and ions as acid and base particles – with more progress than many chemistry teachers or lecturers nearly 100 years later.

3.3. One way of introducing Broensted acids and bases

The famous "Chemical Triangle" (see **Figure 1**) by Johnstone (2000) shows the level of substances ("macro-level"), separated from the level of the smallest particles and chemical structures ("sub-micro level"), finally going to the level of symbols ("representational level"). Students work successfully if they observe firstly substances and reactions on the macro level, then interpret those observations by looking at the involved particles and chemical structures on the sub-micro level, and in the third step express those structures by symbols like formulas and equations on the representational level. Johnstone emphasized that the direct transition from the macro level to the representational level with all formulae and equations means learning by heart and only a little understanding of chemistry. Taking the sub-micro level into account with molecular models or sphere packing for crystal structures, chemical understanding is fostered because students can develop mental models from molecular models or models of giant structures. Those mental models help a lot to write and reflect formulas or equations – they can be taken as shortened models of the participating atoms, ions, or molecules.

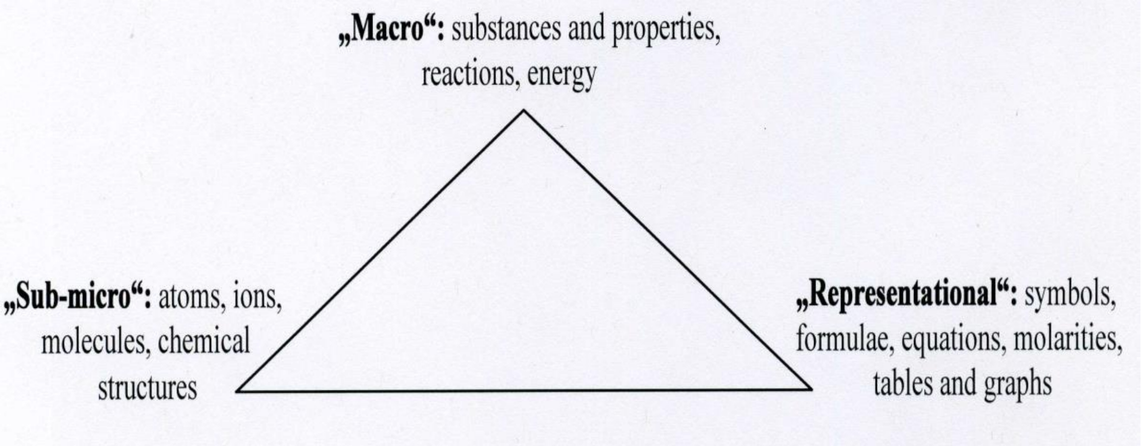

Figure 1. Chemical triangle (Johnstone, 2000).

Based on these fundamental findings, experiments may be the starting point. One way of experimental reflection of the important distinction between HCl molecules in hydrogen chloride gas and $H_3O^+(aq)$ ions as acid particles in hydrochloric acid solution is provided by the classic experiment of the sulfuric acid – sodium chloride reaction: Pure sulfuric acid is added by a dropping funnel to solid sodium chloride in a gas developer and hydrogen chloride gas is stored in a syringe or cylinder. A glass bowl is prepared with tap water which is mixed with a universal indicator – that way, the solution is colored green. Also, a conductivity tester can be prepared. From the syringe, the colorless hydrogen chloride can be routed to the surface of the tap water: just when the color of the indicator changes to read the tester shows a big increase in electrical conductivity. In both reactions, several Broensted acids and bases are involved: they should be illustrated for better understanding on the submicron level with molecular models (see **Figure 2**).

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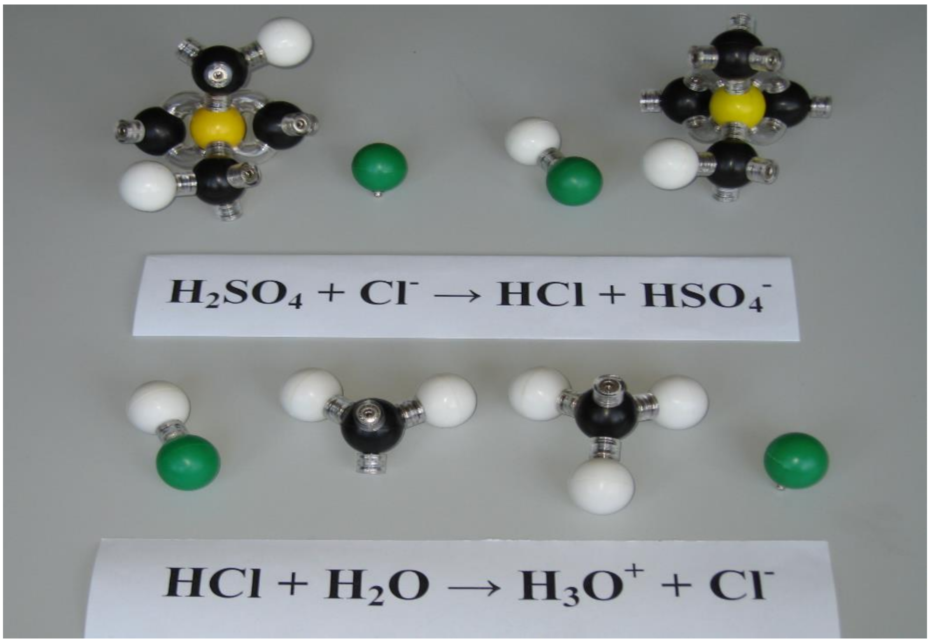


Figure 2. Illustration of two acid-base reactions with molecular models. The figure was taken by Ulrike Henkel from the University of Muenster, Germany.

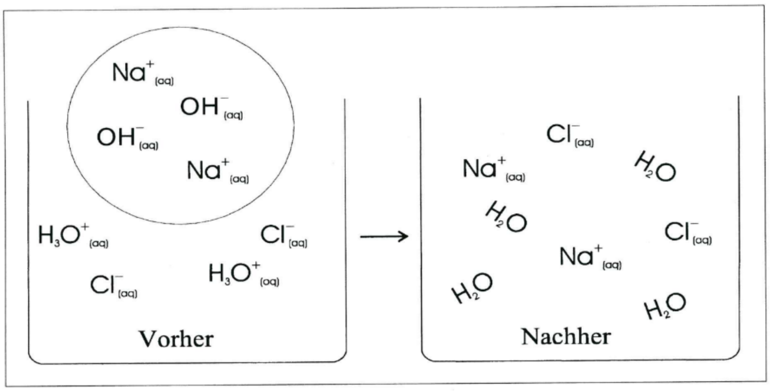
After building and discussing those molecular models, reaction equations can serve as a shortened representation of the models (see **Figure 2**):

sulfuric acid(l)	+	Sodium chloride(s)	→	hydrogen chloride(g)	+	sodium hydrogensulfate(s)
H_2SO_4 molecule	+	Cl^- ion	→	HCl molecule	+	HSO_4^- ion
acid1		base2	→	acid2		base1
hydrogen chloride(g)	+	water(l)	→	hydrochloric acid (aq)		
HCl molecule	+	H_2O molecule	→	H_3O^+(aq) ion	+	Cl^-(aq) ion
acid1		base2	→	acid2		base1

After identification of the involved molecules and ions as acid and base particles, special beaker models can help to understand separated ions in solutions (see **Figure 3**): models of diluted hydrochloric acid, sodium hydroxide solution, and sodium chloride solution are shown. It should be noted that in hydrochloric acid, the H_3O^+(aq) ions are the acid particles, and in sodium hydroxide solution, the OH^-(aq) ions are the base particles. The (aq) symbol helps the learners to get the idea that the charge in hydrated ions is shielded and those ions can move freely in the solution – they are not linked to an ionic lattice-like in solid sodium chloride. Other well-known reactions such as sodium hydroxide-water, ammonia-water, and ammonia-hydrogen chloride may follow to acquire more experience with acid-base reactions. The last-mentioned reaction is particularly the acid-base reaction without the involvement of water molecules:

hydrogen chloride(g) + ammonia(g) → ammonium chloride(s)

HCl molecule + NH_3 molecule → NH_4^+ ion + Cl^- ion



acid1 base2 → acid2 base1

Figure 3. Beaker model to visualize the neutralization of hydrochloric acid with sodium hydroxide solution.

3.3.1. Neutralization

After the experiment of mixing hydrochloric acid and sodium hydroxide solution and observing the exothermic reaction an initial beaker model is drawn (see **Figure 3**) – before the reaction of $H_3O^+(aq)$ ions and $OH^-(aq)$ ions is formulated. On the macro level, the following reaction equation may be quoted in words:

hydrochloric acid (aq) + sodium hydroxide (aq) → sodium chloride (aq) + water

After that, the beaker model should be developed on the submicron level (see **Figure 3**) and finally, after identifying the involved smallest particles, equations are created on the third level:

$$H_3O^+(aq) + Cl^-(aq) + Na^+(aq) + OH^-(aq) \rightarrow Na^+(aq) + Cl^-(aq) + 2\,H_2O(aq)$$

or:

$$H_3O^+(aq) + OH^-(aq) \rightarrow 2\,H_2O(aq)$$

In particular, it should be emphasized that for interpreting the neutralization reaction and the observed decrease of electric conductivity (see **Figures 4 and 5**) not the number of ions gets smaller – but the $H_3O^+(aq)$ ions are replaced by $Na^+(aq)$ ions. In **Figure 3**, the beaker model shows four ions before the neutralization and four ions after the reaction: the conductivity tester indicates the good conductivity of $H_3O^+(aq)$ ions before the neutralization and the decreasing conductivity during neutralization due to the replacing $Na^+(aq)$ ions.

3.3.2. pH values

To convey the idea of pH, the ionic product must be comprehended. We first compare the autoionization of H_2O molecules by this equilibrium:

$$H_2O + H_2O \leftrightarrows H_3O^+(aq) + OH^-(aq)$$

Now we come to the fact that both ion concentrations depend on each other. Experts measured some concentrations at the temperature of 25°C, and the result is the familiar hyperbola (see **Figure 6**):

$$c(H_3O^+) \times c(OH^-) = 10^{-14}$$

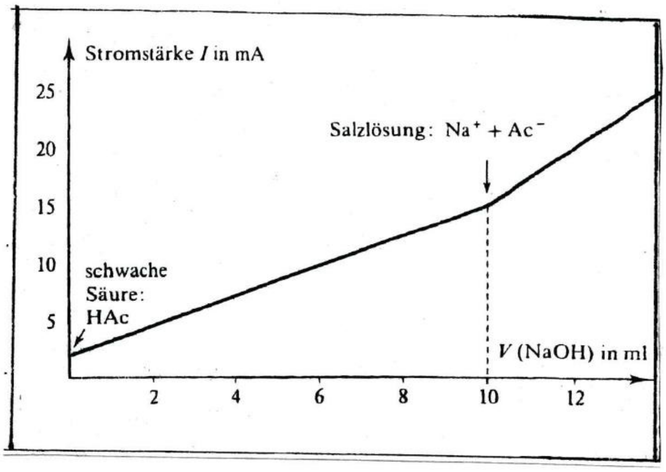


Figure 4. Conductivity curves by neutralizing 0.1-M hydrochloric acid.

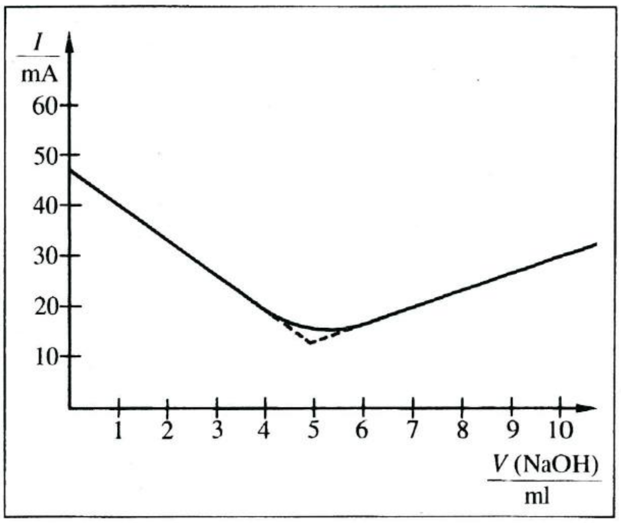


Figure 5. Conductivity curves by neutralizing 0.1-M acetic acid.

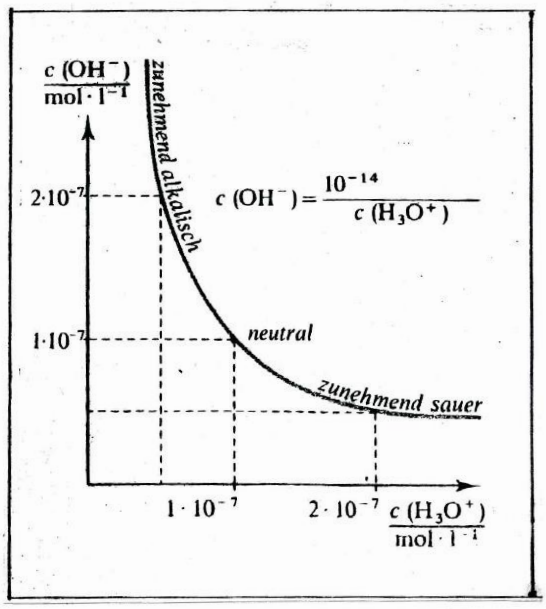


Figure 6. Correlation of H_3O^+ and OH^- concentrations.

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As the equilibrium is valid for all aqueous solutions, the definition of the pH can be derived either from the concentration of H_3O^+(aq) ions or of OH^-(aq) ions. The pH is determined by the concentration of H_3O^+(aq) ions – taking the logarithmic function: if the concentration is c(H_3O^+(aq) ions) = 10^{-2} mol/L, the pH is defined as 2.

3.3.3. Weak acids

If we examine the pH values of 0.1-molar hydrochloric acid and 0.1-molar acetic acid solution, we obtain the values 1 and 3: the concentrations of H_3O^+(aq) ions differ by a factor of 100. Looking at the conductivity in the neutralization of both solutions with sodium hydroxide solution, the results are completely different graphs (see **Figure 4**). These observations can only be explained by the fact that acetic acid solution shows an equilibrium between molecules and ions which lies strongly on the side of the molecules:

$$HAc(aq) + H_2O \leftrightarrows H_3O^+(aq) + Ac^-(aq)$$

To illustrate the existence of molecules and ions in solutions of weak acids, beaker models are again used (see **Figure 7**). It must be clarified that with a degree of protolysis of about 1% for the diluted acetic acid solution, the model must show 99 HAc molecules before one H_3O^+(aq) ion and one Ac^-(aq) ion is symbolized. For the model of the hydrogen sulfide solution, the number of 999 H_2S molecules per one H_3O^+(aq) ion and one HS^-(aq) ion should be symbolized: this way, the degree of protolysis of 0.1% is illustrated. The beaker models thus serve to clear the concept of protolysis degree and equilibrium for learners, to prepare the very difficult concept of equilibrium constants like K_S and K_B constants, and to develop a scientific mental model.

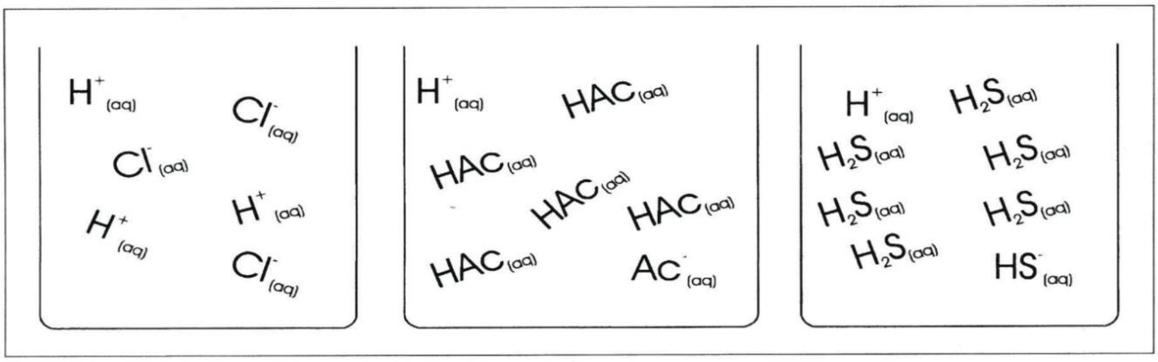

Figure 7. Beaker models of strong hydrochloric acid and two solutions of weak acids.

3.4. Discussion

One likes to quote the advantages of Broensted's acid-base theory – but mixes the argumentation with ideas of Arrhenius' theory: protolysis and degree of protolysis (Broensted) with dissociation and degree of dissociation (Arrhenius), one speaks of substances as acids and bases instead of the involved molecules or ions ("sulfuric acid gives two protons, water is an ampholyte"), or takes the "salt formation" as a criterion for neutralization.

Broensted with his famous fundamental equation A $\leftrightarrows$ B + H^+ gave the symbols A and B always the meaning of molecules or ions – and thus the theory got the important sense. So, for teaching and instruction, it makes sense to designate molecules and ions, which act in reactions as proton donors or acceptors, which can act as ampholytes, and which are defined as conjugated acid-base pairs.

If the teacher helps to look at the particles which are reacting by emitting or taking protons, and if the teacher works with molecular models and beaker models, the learners will develop scientific mental models, will better understand formulas and equations, and will better understand chemistry!

The same basics are valid for understanding redox reactions: teachers have to look to atoms, ions, or molecules which donate electrons, and to atoms, ions, or molecules that accept electrons (Barke, 2012). Also, from suitable concrete models (Barke, 2012), students will create their mental models and will not blame chemistry as a very difficult subject.

4. CONCLUSION

This study was to show a short literature review on Broensted Acids and Bases, in which it explains the history of this theory and what application today is available. This study will be important to give crucial information to students, educators, teachers, as well as researchers.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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