ORGANIC REACTION MECHANISM CONTROVERSY: PEDAGOGICAL IMPLICATIONS FOR CHEMICAL EDUCATION

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ABSTRACT

The paper investigated the pedagogical implications of the controversy generated by the nature of reaction mechanism in organic chemistry as to whether it can be proven or not. A conference of a chemist, chemical educator, a graduate chemistry teacher and a graduate assistant was organized. The conference lasted for four weeks of two interactions per week. Each interaction took three hours. Interactions during the conference took a total of 24 hours (8x3). A postgraduate student recorded minutes of each interaction. The minutes of the total interactions served as the source of information for the discourse in the study. While the chemist treated reaction mechanism as a fact supported by experimental evidences, the chemical educator was conscious of reaction mechanism as a theory which can be refuted. The students were not sure of the nature of reaction mechanisms. These were discussed in the study presented below. *[AJCE, 2(2), February 2012]*

INTRODUCTION

Chemical reactions are common in chemistry and related disciplines. In fact, chemists study chemical reactions. Chemical reactions can be simple or complicated to understand. For example, a reaction that simply goes from A to B or from B to A may be easy to understand. However, there are so many chemical reactions notably in organic chemistry where reactions may not directly lead to products. Some complexes may form between reactants and products which will make it difficult to understand reaction pathways to products.

Khan and Khan (1)) defined reaction mechanism as "a step-by-step description of the events taking place in a chemical reaction". It is a theoretical framework accounting for the fate of bonding elections and illustrates which bonds are broken and which are formed. For example in the chlorination of methane to give chloromethane:

$$Cl:\mathrm{Cl} \quad \mathrm{hv} \quad 2\,\dot{\mathrm{C}}l \text{ (Initiation, homolytic fission of the chlorine molecle)}$$

$$\text{Step 1:} \quad \dot{\mathrm{C}}\mathrm{l} + \mathrm{CH_4} \longrightarrow \dot{\mathrm{C}}H_3 + \mathrm{HCl}$$

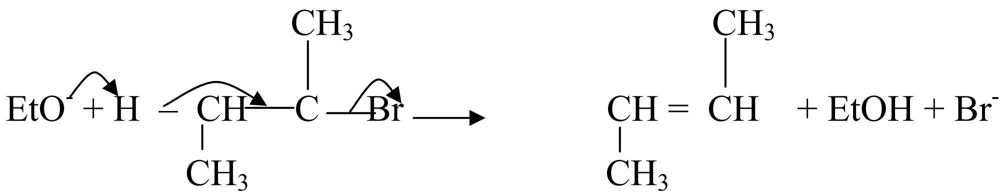
$$\text{Step 2:} \quad \dot{\mathrm{C}}H_3 + \mathrm{Cl_2} \longrightarrow \mathrm{CH_3Cl} + \dot{\mathrm{C}}l$$

$$\textit{Step } 3: \quad \dot{\mathrm{C}}l + \mathrm{CH_3}cl \longrightarrow \dot{\mathrm{C}}H_2Cl + \mathrm{HCl}$$

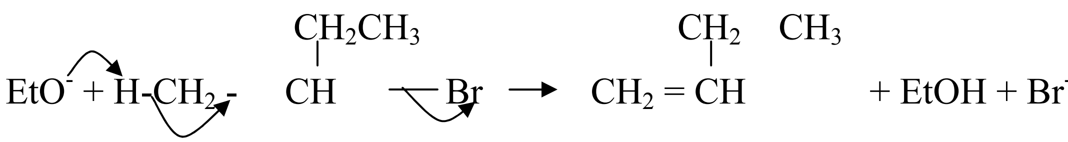
$$\text{Step 4:} \quad \mathrm{Cl_2} + \dot{\mathrm{C}}H_2Cl \longrightarrow \mathrm{CH_2}Cl_2 + \dot{C}l$$

and so on leading to a mixture of all the possible chlorination products. This is simple and straight forward, but how do you prove to the students the existence of free radicals involved in the mechanism?

A little more complex example is the dehydrogenation of an alkyl halide to yield more than one alkenes, namely:



2 – Bromobutane   But -2-ene (main product)



But -1-ene

Steps in the production of the alkenes are not of interest here, but the direction of the curved arrows and the formation of bonds. There are concepts that support these ideas but can they be proven to the understanding of the learner? Clugston and Flemming (2) in discussing the relationship between order and reaction mechanism described reaction mechanism as a detailed step-by-step account of how an overall reaction happens. It specifically indicates all intermediate states and mentions all intermediate species formed, even though some do not appear as products. Information about orders of reactions is derived from experimental data.

In this sense, reaction mechanisms are studied. Generally, chemical reactions involve breaking and making of bonds between atoms and molecules, and possible realignment of atoms, ions and molecules. A chemist is particularly interested in reaction mechanisms which are the totality of what happens during chemical reactions. The chemist takes an anatomical view of what happens during chemical reactions: what bonds were broken? What bonds are formed? Is there a complex that is formed before product? What realignment of atoms, molecules and ions are noticed including free radicals?

Of recent, reaction mechanisms have been of concern to chemical educators. The pedagogical issue is that we should be mindful about what we teach the students. When real situation is mentioned in passing instructions to a novice, one can concretize such situation for meaningful understanding and learning. For example, telling a chemistry student and showing him a sample of copper II tetraoxosulphate VI will help him. But telling the student about an atom or ion and showing the student a model of such- as is the case of chemistry: Green and Rollnick (3)-will not help. This is because the model is not an atom or ion. In this context, reaction mechanisms in chemistry textbooks that we teach the students have come under serious criticisms.

One of such criticisms is that of whether or not reaction mechanism can be proved. Chemists are satisfied with the study of reaction mechanism as provided by the chemistry syllabus or course work. Chemical educators are worried about rote learning that will result from the chemists' point of view. Some controversy has arisen that need to be properly examined.

THE CONTROVERSY

Controversy is likened to an argument that is generated by individuals' various suggestions and opinions about an issue. The very nature of a controversial issue is that there is more than one defensible position that can be taken (4). When dealing with controversial issues it is important to uncover how particular knowledge claims may serve the interests of different claimants. Reaction mechanism is one such issue in organic chemistry that has attracted a lot of controversial comments from some members of the scientific community. Most organic chemistry textbooks commonly teach that reaction mechanisms can never be proven. But Buskirk and Baradaran (5) have reasons to argue that reaction mechanisms can only be proven false. They further argued that there is a philosophical limitation on our ability to prove chemical reaction mechanisms. According to them, “mechanisms cannot be proven with philosophical certainty”.

Brown (6) considered reaction mechanisms from its theoretical point of view. He posited that a theory that has been tested by many different experiments that could have in principle proven it to be incorrect is a better explanation for having been so tested. He concluded that it is possible to devise a useful confirmatory experiment for a reaction mechanism considering the general form of the potential energy surface over which a chemical reaction proceeds.

Lewis (7) focused on the general nature of proof as providing absolute certainty of truth. According to him, most professional chemists use the legal definition of proof when they accept evidence for or against a particular hypothesis or theory. He suggested that at some point, the experimental (circumstantial) evidence in favor of the mechanism under study becomes overwhelming, and at that point one might argue with considerable justification that the mechanisms have been proved beyond a reasonable doubt. He seems to be saying that failure to be falsified by repeated experiments is one hallmark that is used to elevate a hypothesis to the status of a theory, and in this aspect a well-tested reaction mechanism is more akin to a theory than a hypothesis.

Yoon (8) drew our attention to Thomas Kuhn’s philosophy that the value of a scientific theory rests upon its ability to predict future outcomes. Theories that are supported by repeated experimental validation become accepted as paradigms which succumb to falsification only with great difficulty. Yoon (8) opined that experimental chemists perform experiments designed to corroborate mechanistic hypothesis. He argued that techniques such as molecular beam and femtosecond spectroscopy allow us to gain insights into reaction mechanisms that were inaccessible using classical kinetic methods alone. There is no amount of technological sophistication that will limit our insight to the over abundance of possible alternate explanations for any given discrete data available for probing reaction mechanisms.

As part of the controversy by the question: “Can reaction mechanisms be proven?” Wade (9) declared in categorical terms that:

> “I take strong exception with Buskirk and Baradaran’s premise that mechanism can now be proven – the current usage of well-established seems to Buskirk and Baradaran’s suggested use of proven. However, it is my opinion that exchanging “proven” for “well-established” is a step backward in science. I plan to continue accepting mechanisms as well-established but not provable and doing chemistry rather than philosophy”.

Chemists, educators and students are entitled to their mental constructs about reaction mechanism in the classroom. What pedagogical implications have these knowledge claims for teaching and learning reaction mechanisms in organic chemistry? This is the main interest of the paper. Thus three questions were critically considered in the paper, namely:

(1) What is the view of the chemist on the nature of reaction mechanism?

(2) What does the chemistry teacher think about teaching and learning reaction mechanism?

(3) How do the students feel about learning reaction mechanism?

METHODOLOGY

A face-to-face conference of chemists, chemistry teachers and students was organized to discuss the nature of reaction mechanism and implications for science education. A professor of organic chemistry, a professor of science education, a graduate chemistry teacher (who has had the experience of teaching senior secondary students for eight years), a graduate assistant pursuing a master’s degree in an aspect of organic chemistry and two final year chemistry students (specializing in organic chemistry) were invited for the conference. The exercise spanned a period of four weeks with circulars for a meeting sent to participants eight times. Each conference meeting lasted for three hours.

The investigator started the initial discussion with the argument of Brown (6), Lewis (7), Yoon (8) and Wade (9) on the question asked by Buskirk and Baradaran (5), namely "Can reaction mechanism be proven? Participants brainstormed on the following sub-questions, namely:

(i) What is reaction mechanism?

(ii) What evidence exists for acceptance of reaction mechanism?

(iii) How do we learn reaction mechanism?

(iv) What are the contributions of theories to reaction mechanisms?

(v) What facts are associated with reaction mechanisms?

(vi) How do chemists arrive at reaction mechanisms?

(vii) Can we prove reaction mechanisms?

The professor of organic chemistry provided an insight into reaction mechanism in organic chemistry and guided our discussions to conceptions and misconceptions as thought by the other participants. The professor of science education was particularly interested in the pedagogical implications arising from the controversy of teaching and learning reaction mechanisms. The graduate assistant, chemistry teacher and final year chemistry students were involved in the discussion to express their views about learning reaction mechanism after hearing from the chemist and the science educator. The chemistry teacher apart from presenting his view was also requested to make suggestions as to what he thought should be done to help students learn reaction mechanism. A postgraduate science education student was invited to take minutes for each session and also acted as the rapporteur. Altogether the postgraduate student recorded eight comprehensive minutes which formed basis for the discourse.

FINDINGS

Excerpts emerging from the discussion of the chemist, chemical educator and the graduate chemistry teacher concerning reaction mechanisms were carefully examined and presented, thus:

Chemist:

> Reaction mechanism, we chemists know, is central to learning how things work in chemistry. … I mean fundamental concepts associated with formation of radicals, release and acceptance of electrons, bond breaking and making must be known. Even when experiments are carried out and analyses done, we need extra knowledge to understand what is going on. Ascertaining reaction mechanism is the project of a chemist, carried out over a period of time and found to be reliable.

Chemical educator:

> There are numerous chemistry textbooks for teaching and learning. …The books have their different interpretations for reaction mechanisms. …Reaction mechanisms by Peter Sykes is a good one…We don't teach students how to prove reaction mechanism; rather they learn it. …Most students can't grapple with the associated concepts; they memorize and do a lot of guess work.

Graduate chemistry teacher:

> Students are taught to define reaction mechanisms. … What they learn is limited in their syllabus and nothing more; mechanism is quite difficult for students.

It was noted from the interactions in the recorded minutes of the conference that:

(i) The chemists' emphasis was on the content of chemistry. He talked more about facts, concepts, principles and laws. He harped so much on the experimental evidences supporting reaction mechanisms. He talked about the ability of the students to apply the theories associated with reaction mechanisms. The chemist emphasized the rigid principles governing reaction mechanisms based on the theoretical nature of reaction mechanism. "Even though what transpire in between the complexes are not visible to our eyes, there are crown evidences that they happen" the chemist stated.

(ii) The chemical educator was particularly conscious of the teaching aspects of reaction mechanism. He stated that reaction mechanisms could be taught according to the chemistry course content and as contained in current chemistry textbooks, but chemistry teachers should watch out for current information in journals and internet with the view of making changes. He continuously sighted some scientific philosophies of Thomas Kuhn and Karl Popper concerning paradigm shift and fallibilism. The main concern of the chemical educator was that students will end up "learning to pass examination-related reaction mechanism and not understanding what it was all about". The chemical educator was particularly interested in the theoretical nature of reaction mechanisms. He stated that students need to learn it and meaningfully understand it the way it is. He noted the difficulties students encountered in learning kinetics which is important in determining reaction mechanisms. He stated that kinetics is the best tool for predicting or eliminating mechanisms under consideration since an observed reaction rate must satisfy the proposed mechanism.

(iii)The graduate chemistry teacher did not say much about the teaching of reaction mechanism at the senior secondary school level. Our interactions in the conference showed that he had some knowledge of reaction mechanisms having obtained a degree in chemistry education in one of the best universities in Nigeria. The graduate assistant was regarded as a chemistry student. The graduate chemistry teacher, graduate assistant and final year chemistry students' views were taken as those of chemistry students. Our interactions with them in the conference showed that they did not find it easy learning reaction mechanisms. The students showed good understanding of reaction mechanisms and constantly sighted textbooks to prove that they knew what they were saying. When confronted with the question: “Do you think that the mechanisms can be proved”, they followed with question. “How? “We learnt it the way it is in the textbook” was their answer. Further argument showed that they were satisfied learning reaction mechanism as a fact and not a theory.

THE DISCOURSE

As a chemistry student, I was particularly interested in memorizing reaction mechanisms so as to pass related chemistry courses without understanding the nitty-gritty of such mechanisms. I guess that there are so many chemistry students that were like me and even today many chemistry students do not understand reaction mechanisms. As a chemistry teacher and an educator, I look back at those days and recall all the pains and efforts made to understand reaction mechanisms and the problems my students will have to grapple with direction of arrows and either electrons grabbed or shared with atoms or ions. I also try to imagine how my students feel about the breaking and making of bonds as related to electrons. Discourse of Green and Rollnick (3), Sykes (10), and Bhattacharyya and Bodner (11) on these issues lend credence to my experiences and observations. The graduate assistant and the chemistry teacher that participated in the conference corroborated these experiences in their views.

One of the aims of the chemistry syllabus is to provide adequate foundation for post-secondary chemistry course (WAEC, 12). In this regard, some elements of reaction mechanism in organic chemistry included in the syllabus are simply examples of addition and substitution reaction, properties of the – OH group as functional group, inter-convention of the various forms of carbohydrates to mention a few. These impose high cognitive demand on the students. Interactions with the students that participated in the conference showed that their reasoning at the abstract level was limited. It was also gathered that not all the students taking such chemistry courses requiring mechanisms are at the formal abstract level of gazing into space to make out how bonds are formed and how bonds are broken.

It is worth noting that tertiary teachers have problem in teaching reaction mechanisms. Without doubt students' difficulties in learning and understanding reaction mechanism will arise from the teachers' handicap. Teaching reaction mechanism will require teachers' thorough knowledge of: (i) theoretical basis of reaction mechanism, (ii) experimental basis of reaction mechanism, (iii) facilities available for studying reaction mechanism, and (iv) students' readiness to learn reaction mechanism. These issues are considered as part of the teachers' pedagogical content knowledge-distinctive body of knowledge for teaching and as the professional knowledge base of teachers (13).

A chemical educator has the training of a chemist and that of an educator. An effective chemistry teacher must be armed with the content and process of chemistry. The teacher must also posses the adequate pedagogical know-how to be able to impart knowledge in the content and process area. Part of the course taken by the chemical educator in training is the "History and philosophy of Science and Science Teaching". The course is designed to acquaint the trainee chemistry teacher with contemporary views of the nature of science and scientific inquiry, and to relate these views to issues concerned in the teaching of science in schools and the school curriculum. Particular emphasis is given to the viewpoints advanced by various philosophers of science and the role such philosophical consideration should play in the professional training of science teachers including chemistry teachers.

Wade (9) has emphatically stated that chemistry is not philosophy; chemistry should be taught as chemistry, and philosophy as philosophy. In rationalizing and justifying theories in chemistry, philosophical knowledge is relevant. For example, central to reaction mechanisms is the transition state theory. This theory is applied to the activated complex or the transition state. It makes use of the concepts of equilibrium constant and free energy. As related to the study of reaction mechanisms, the activated complex is regarded as being like a molecule even though its life time is very short, and it cannot be studied as a chemical species. In spite of this, the idea of thinking of the activated complex as being in equilibrium with the reactants proves useful (14).

Another useful theory in reaction mechanism is the collision theory of reactions. This theory states that molecules must physically meet before they can react and that molecules must collide with sufficient energy for reaction to take place. The teacher must understand and know how to apply these theories in order to relate them properly to reaction mechanism.

According to the chemist (professor of organic chemistry), during the conference emphasized that these theories were guiding principles in studying reaction mechanism. Students have to learn them the way they are so as to understand reaction mechanism. Reaction can be conceived through experimental evidences but cannot be proved. If this is the case, how will a teacher grapple with the issue of convincing the students?

Buskirk and Baradaran (5) despite all the modern techniques that provide macroscopic evidences about reaction mechanisms recognized the pedagogical problems associated with unproven nature of reaction mechanisms philosophically and suggested that:

> “It is important to remind students that reaction mechanisms are theories not facts. They should not be believed dogmatically and are open to refutation by later work. We fear, however, that the idea that mechanisms can never be proven or even supported by evidence will discourage students from using all the tools at their disposal. We should continue to encourage students to seek confirmation of their mechanistic hypothesis and use theories for which there is the most support”.

A conscientious teacher should have to rethink about the currency of his/her chemical knowledge. One useful thing about the philosophy of chemistry, like any other science discipline, is that it seeks the justification of the status of theories in teaching and learning processes. Theories are central in development and growth of scientific knowledge, including chemical knowledge. Facts are important but we must remember they are theory-laden as we are told by Karl Popper. Hypotheses are constructs that form part of the development trend of theories. We have also been told that successful theories are continuously facing threat from possible crisis in the chemical society like any other scientific community. As teachers, we still make our students to depend on induction and recognize that successful tests of theory constitute support for it. We also believe that observations are theory-laden just as facts. So whenever we make an observation, we rely on theories and assumptions beyond those that we are testing.

Reaction mechanisms are mental constructs derived from experimental evidences about how a reaction proceeds. These mechanisms as we know in chemical reaction lend themselves to alternative pathways depending on which reagents are involved. However, what is of interest is not the effect of the reagents but the mechanism as bonds are broken and made related to electron transfer, acceptance, rejection, atom and charges. The implication of this is that for the purpose of learning and understanding, the teacher uses a model to illustrate issues related to reaction mechanisms. Such models do not portray reality rather they serve as “instructional way out” of the problem for the teacher. This is the conviction of the teacher which gives him the confidence to continue giving instruction of the reality of reaction mechanisms equivalent to proveness of reaction mechanisms. To what extent can we convince the learner chemist for meaningful learning as to proving reaction mechanisms to be true? On the other hand, will instructions benefit the learner if we continue to refute existing reaction mechanisms for the sake of knowledge? Is this built into the framework of the course outline of the students in the related chemistry course? The choice is clear-teaching chemistry or teaching philosophy. We do know that the essence of philosophy of science is to enhance rational understanding of chemical principles. Of what use will it be to the teacher especially in the case of proving the efficacy of a reaction mechanism of reactants to products?

CONCLUSION

Chemistry teachers teach reaction mechanisms as in textbooks using guiding principles students may understand or not. At the advanced level experimental evidences are presented to learner to support reaction mechanisms. The student is interested in passing related examinations without meaningful understanding. Students are not interested in finding out whether reaction mechanism can be proven or not. Chemists do not concern themselves with the proven nature of reaction mechanisms as long as there are guiding principles for learning them. The controversy arising from the proven nature of reaction mechanisms will persist. We may need to tow the line of the chemical educator who insists on currency of information regarding reaction mechanism because of pedagogical implications.

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