A Nontraditional Laboratory Proposal: Investigating the Kinetics of a Chemical Reaction

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Abstract: This paper presents an unstructured laboratory in which students determine the rate law for a reaction. We have selected for this investigation the reaction between magnesium and hydrochloric acid. The general goal of the proposal is threefold: (1) to increase students' interest in science during first-year chemistry; (2) to create a more active learning environment where students can learn and do science as scientists; and (3) to develop and promote critical thinking, analytical reasoning, collaboration, and interactive discussion based on a scientific problem. This laboratory has proven to be effective because the students, with some guidance from the instructor, were able to (1) state one or more hypotheses related to the problem under study (chemical kinetics); (2) design procedures and strategies to answer specific questions; and (3) establish methods to manipulate and interpret the data. Finally, the students were required to write a report. In this way, the laboratory promotes creativity and improves students' critical thinking in an introductory course of university general chemistry.

Teaching experimental science at the college level traditionally involves having students complete well-established fool-proof laboratories. In general, in the chemistry curriculum at Comahue National University, similar to other universities in Argentina, laboratory sessions are carried out parallel to all theory lectures, and they are used to close each topic and to solidify the concepts presented in lecture. In such activities, there is a standard structure, in which students follow printed instructions (laboratory guide or "cookbook"), complemented by the instructor's verbal comments. In this way, laboratories can be easily completed in the time available, but students associate them only with a specific topic, making each subject appear isolated from other ones. This method, which has been used extensively, does not yield integrated conceptual learning. Probably, in beginning science courses, the set of instructions for the laboratory session are carried out automatically, leading to "the right answer." Of course, the participation of the instructor during the performance of traditional laboratories guides the students and avoids misunderstandings. It can be more effective to propose activities in which the students, based on a true motivation, follow their own decision criteria. These activities will be those that allow science learning in a scientific environment [1, 2]. Thus, an alternative to the traditional method has been to use active-learning methods, that is, to enhance the motivation of the students by means of an unstructured laboratory exercise. Open and dynamic proposals related to nontraditional laboratory activities have been reported by several authors [2–6].

In this article, we report a laboratory proposal that includes the introduction of a problem and requires the active participation of the students in several activities, including making hypotheses and predictions, designing experimental setups, recording observations, collecting data, interpreting measurements, and writing reports. Similar to proposals of other authors [4–6], our proposal involves significant changes in the role of both students and instructors as opposed to the traditional laboratory. The instructor is not the source of the information, and his or her role is to ensure that the students become acquainted with the methods that scientists use.

The general goal of this proposal is threefold: (1) to increase students' interest in science during first-year chemistry; (2) to create a more active learning environment where the students learn and do science as scientists; and (3) to develop and promote critical thinking, analytical reasoning, collaboration, and interactive discussion. These ideas were applied in a laboratory experiment for which the specific goal was to determine the rate law of a chemical reaction. In particular, we have selected for this investigation the reaction between magnesium and hydrochloric acid. The net ionic equation is

$$Mg(s) + 2H^+(aq) \longrightarrow Mg^{2+}(aq) + H_2(g) \qquad (1)$$

Our students are already acquainted with this reaction; they have used it in another laboratory experiment [7] where they determine the molar volume of hydrogen gas. The rate of this reaction can be evaluated using different experimental procedures. It is possible to determine the reaction rate by measuring the time required to collect a measured volume of hydrogen gas [8, 9], by monitoring the rate of hydrogen ion disappearance by titration over time [8], and by measuring the time required for the complete consumption of a known amount of magnesium [8]. Another alternative is to measure the partial pressure of hydrogen gas as a function of time, but this requires more-sophisticated equipment [10]. The characteristics of the selected reaction allow students to

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propose different procedures for the experimental determination of the reaction rate.

The laboratory presented was performed during consecutive years by introductory chemistry students at Comahue National University. Approximately 30 students per year enroll in this course, which includes two hours of lecture and three hours of laboratory or problem solving per week. The following describes the experimental and theoretical work developed with our students. They spent two laboratory sessions (about three hours each) performing this laboratory. The activities are carried out in groups of two or three. This nontraditional laboratory activity was intermixed with traditional laboratories, and the students' opinions of this assignment were very positive.

The laboratory was presented in three stages, although a different structure could be followed. The first and second stages were started by each group after leading questions were asked by the instructor to trigger the students' reasoning and actions. During the third stage, all the groups were invited to share and discuss the results.

Stage 1. The specific goal of Stage 1 is to identify the factors that affect the reaction rate. The students are asked the following questions. How can the rate of a chemical reaction be defined or expressed? How can this reaction rate be measured? Which factors affect the rate of reaction?

Prior to any systematic measurement and in order to determine what measurements are needed, each group discusses and answers the stated questions. Occasionally, some preliminary tests are performed to assist their reasoning. It is very important to allow the students to plan the experiments and to select the laboratory materials and equipment useful for testing their hypotheses.

The most common student proposal for evaluating the reaction rate is to measure the required time for the complete consumption of a known amount of magnesium. In this case, the reaction rate (an average value) was expressed as the ratio between the amount of magnesium reacted (in moles) and the time for this reaction (in seconds). Other proposals are discussed with the instructor, but will not be presented here.

When considering the factors affecting the reaction rate, one of the hypotheses commonly proposed by the students is that the rate of the reaction shown in eq 1 is a function of the concentration of hydrochloric acid. Taking into account that this reaction involves a heterogeneous system, some characteristic of magnesium solid should affect the rate. This idea does not appear spontaneously. Coached by the instructor, the students are stimulated to think of those characteristics of the solid that can affect the reaction rate. Students start by proposing the mass and the surface area of magnesium. They have the opportunity to test their proposals by changing these variables because magnesium is available commercially in different forms (e.g., strips, powder, shavings, chips).

To determine the characteristic of magnesium that influences the reaction rate, students change the surface area or the mass of the metal at constant hydrochloric acid concentration. The acid concentration is selected to assure a stoichiometric excess with respect to the amount of magnesium, so as to maintain a constant hydrogen ion concentration during the reaction. The experiments are performed using different morphologies of magnesium (different surface areas) at constant mass and using equal areas of magnesium with different masses (sheets of different thickness). This group of measurements shows that the surface area of magnesium is the key factor affecting the reaction rate. Once the students reached this conclusion, they propose the following rate law

$$\text{rate} = A[\text{H}^+]$$

where A is the magnesium surface area and $[\text{H}^+]$ is the hydrogen ion concentration. An improved expression is suggested by the instructor

$$\text{rate} = kA^a[\text{H}^+]^b \quad (2)$$

which includes a proportionality constant, k, and accounts, through the parameters a and b, for a possible nonlinear dependence. This expression is easily accepted by the students after some discussion among all the groups.

The original rate law proposed by the students, without k, a, and b, gives only qualitative agreement with the preliminary observations, but it is the starting point that motivates the students to do a more detailed investigation.

Stage 2. The specific goal of Stage 2 is to determine the quantitative effect of the experimental variables on the reaction rate. The following questions are asked. What is the dependence of the reaction rate on the hydrochloric acid concentration? What is the dependence of the reaction rate on the surface area of magnesium? How can each effect be separated in order to be studied independently?

The goal is now to determine the values of k, a and b. Before performing any experiments, the instructor and the students discuss the experimental procedure for separately studying the effect of each reactant on the reaction rate. Hence, from the rate law, the necessity of keeping one effect constant while the other one changes is proposed and easily accepted by the students. So, the reaction rate equation can now be written alternatively as

$$\text{rate} = K_1A^a \quad (3)$$

or

$$\text{rate} = K_2[\text{H}^+]^b \quad (4)$$

for constant $[\text{H}^+]$ or constant magnesium surface area, respectively. The procedures to separately investigate the effect of each reactant are as follows. To determine the effect of magnesium surface area, most students select magnesium strips. They perform measurements of the reaction rate using a constant hydrochloric acid concentration and different magnesium surface areas (equivalent to using different lengths of magnesium strip). In all cases, the magnesium mass is limiting with respect to hydrochloric acid concentration. To quantify the effect of the concentration of hydrochloric acid solution on the reaction rate, the students change the solution concentration at constant reactive area of magnesium. The majority of students again select magnesium strips, because they more easily reproduce the same reactive area of magnesium.

For both procedures and prior to any measurement, the mathematical treatment from the separated equations is discussed in all the groups with the instructor's guidance. Then, it is not difficult to show that, after application of

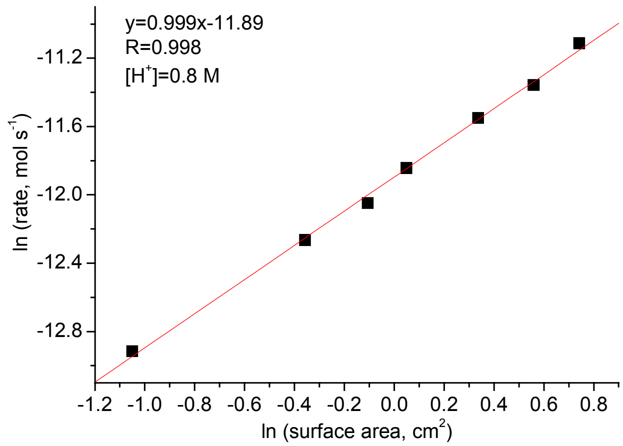

Figure 1. The ln–ln plot used to find the value of *a* for the dependence of the reaction rate on the surface area of magnesium using eq 5.

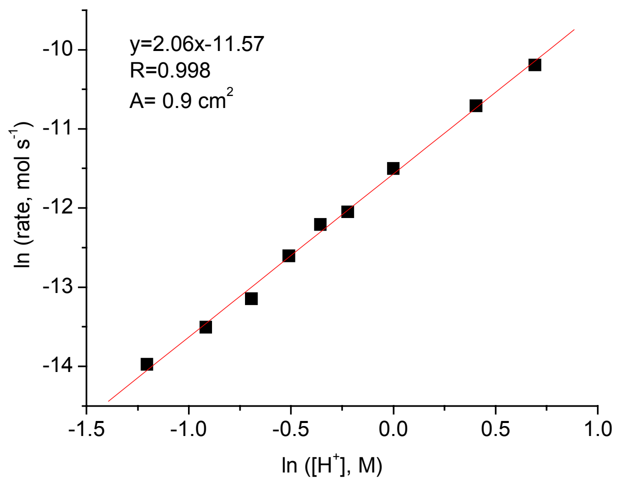

Figure 2. The ln–ln plot used to find the value of *b* for the dependence of the reaction rate on hydrogen ion concentration using eq 6.

logarithms, eqs 3 and 4 can be transformed, respectively, to the following:

$$\ln \text{rate}_i = a\ln A_i + \ln K_1 \quad (5)$$

and

$$\ln \text{rate}_i = b\ln\, [\text{H}^+]_i + \ln K_2 \quad (6)$$

The subscript i indicates the experiment number. Then, the determination of several pairs (rate$_i$, A_i) and (rate$_i$, $[\text{H}^+]_i$) should give, in both cases, straight lines with slopes a and b, respectively.

Student Results

Study of the Dependence of Reaction Rate on the Surface Area of Magnesium. Two aspects of this study are worth discussing with the students. One of them is the need to use a volume and concentration of hydrochloric acid solution that assures stoichiometric excess with respect to magnesium. The other is how to treat the ratio between the surface area and volume of the magnesium strips. Because the density is constant, the area to volume ratio is equivalent to the area to mass ratio, which is constant for different lengths of magnesium strips. Also, because the border strip area is negligible, the reaction area remains practically constant during reaction, as is required for the application of the separated rate equations.

Figure 1 was constructed using eq 5 and representative experimental values of the reaction rate as a function of the surface area of magnesium. The slope is $a = 0.999 \cong 1$.

Study of the Dependence of the Reaction Rate on the Hydrochloric Acid Concentration. Figure 2 shows a plot constructed from student data according to eq 6. The slope, b, is 2.06 or approximately 2.

Stage 3. The specific goal of Stage 3 is to integrate the experimental results with the theoretical concepts and write a report covering the experiments.

The instructor's role in this stage is to coordinate the discussion of the experimental data and the calculations for the results. It is very important to compare the experimental results obtained by each group. Once all the data are analyzed and the representative values for the parameters a and b are accepted, the students realize that their partial results can be generalized into a rate law valid for any experimental condition, that is,

$$\text{rate} = kA[\text{H}^+]^2 \quad (7)$$

In order to calculate the value of k, the students were encouraged to consider the meaning of the y intercepts in Figures 1 and 2, which are ln K_1 and ln K_2. As defined in the derivation of eqs 3 and 4, K_1 and K_2 are constants that correspond to two different experimental conditions: constant hydrogen ion concentration (Figure 1) and constant surface area (Figure 2), respectively. Both constants include k, so either figure allows the calculation. Using $\ln K_1 = \ln (k[\text{H}^+]^b) = \ln [k\,(0.8)^2] = \ln (0.64k)$ and $\ln K_2 = k\text{A}^a = \ln (0.9k)$, we can obtain the two estimates, $k = 1.07 \times 10^{-5}$ mol s^{-1} M^{-2} cm^{-2} and $k = 1.05 \times 10^{-5}$ mol s^{-1} M^{-2} cm^{-2}, respectively. The values of a and b are in agreement with reported data [10]; however, the aim of this activity was not to obtain correct values of a and b. Instead, it was to obtain these values through conceptually correct procedures, which are thought out by the students themselves.

From observation of Figures 1 and 2, the students are encouraged to calculate parameters a and b using pairs of experiments (pairs of points in the figures) in order to realize the advantage of linear fitting for many experimental points over isolated pairs of points.

The final activity in class is a discussion of the experiments from the molecular point of view. This discussion is very appropriate, because this kind of analysis is not necessarily part of the students' reasoning during hypothesis proposal. Visualizing the interaction between hydrogen ion with a surface of magnesium allows the understanding of the dependence of reaction rate on magnesium surface area. At the end of the exercise, the instructor introduces the terminology and the concepts of chemical kinetics. It is possible to define the constant, k, as the *rate constant* and the a and b parameters as *reaction orders*. In subsequent activities, given that the reaction in eq 1 is of second order with respect to hydrogen ion concentration (b is 2), we introduce reaction mechanisms, elemental steps, and collision theory to analyze the possibility of some bimolecular elemental step. In addition, concepts such as activated complex and activation energy are introduced and the possible effect of temperature on reaction rate is discussed. Consideration of the effect of temperature not only allows students to realize that this effect should be included in k, but also shows them that the discovered rate law is valid at room temperature. Then, at room temperature

$$\text{rate (in moles of magnesium per s)} = 1.06 \times 10^{-7} A[H^+]^2$$

At this point, there is enough motivation to plan a future investigation, the effect of temperature on the rate of the reaction in eq 1.

Once the students have completed their work, they are required to write a report.

Conclusions

When the traditional laboratory is used, the students do not have an opportunity to develop scientific procedures and to construct new concepts. In conventional laboratory work, the students verify a concept or principle by following a set of cookbook instructions, almost without any analysis or discussion. Thus, the student's role is reduced to receiving information independent of their previous knowledge; however, if the students are given the opportunity, they are able to determine by themselves, not only the correct answers, but how the answers are reached.

This proposal for the teaching of an experimental science allows the students, under the guidance of the instructor, to achieve significant learning of chemistry. The advantages of this methodology are both general and specific in nature.

The general advantages include the following. The students learn the relevant concepts by using procedures similar to those used in scientific research. They propose hypotheses, suggest and design experiments, collect data using modern instruments or their own experimental setup, analyze the data, and think critically about the data. This stimulates their creativity and places them in control of their own learning.

The cooperative nature of scientific activity is demonstrated because the students participate as a group and compare their results with those of different groups. The data analysis as performed by each group is examined and linked with the experimental results obtained by the other groups, generating an environment of open discussion and systematic evaluation. Then, it is possible to reject or accept the formulated hypotheses based on a wide range of data.

The students not only design their own experiment, which involves several laboratory operations (solution preparations, weighings, gas-volume and time-interval measurements), but they also choose the appropriate laboratory materials.

The students process their data by themselves. This stage teaches the students to use analytical and graphical methods of data analysis.

The nature of this nontraditional laboratory encourages students to perceive the problem. During the laboratory discussion, they are able to provide an interpretation of their own results. Then, the students formulate a concept or principle by means of active participation in laboratory activities. This process allows them to generate a connection between experiments, previous concepts, and the discovered concept.

The use of writing assignments increases the understanding of the concepts [11, 12].

Specific advantages include the following. The chemical concepts covered in this proposal are many: stoichiometry, reactivity, gases, solutions, and, of course, chemical kinetics. The activity integrates these subjects under one objective and not, as traditionally, isolated pieces of knowledge.

Despite the fact that the students lack certain concepts of chemical kinetics, several of them offered hypotheses about factors affecting the rate of reaction and arrived at a mathematical expression of the reaction rate.

The general discussion developed in the third stage generates the possibility of analyzing practical and theoretical concepts related to chemical kinetics. One of the main problems of chemistry teaching is articulation of the relationship between laboratory practice and theory, especially when these activities are associated with different teachers. The challenge is to design proposals where theoretical lectures become necessary to answer questions that originate during previous investigative activities and where theoretical lectures initiate investigative activities. The use of a demonstrative experiment in the classroom is an additional and appropriate resource.

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