The Application of an Activity Relating to the Determination of Avogadro's Number in a Class of First-Year Science Students

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Abstract: Researchers have shown that students have difficulty understanding the concept of the mole and Avogadro's number. The author's opinion is that the reason for this is because they are not aware of the fact that the definitions of the mole and Avogadro's number are based on carbon-12. In this manuscript, an activity based on the use of the mass spectrum of methane for the determination of Avogadro's number and its application in a class of first-year students taking general chemistry is described. The activity consists of, first, determining the mass of a single carbon-12 atom in grams and then, using the definition of a mole, calculating Avogadro's number by dividing 12.00000 g mol^{-1} (carbon-12 mole weight) with this mass. The class was divided into seven groups and from the seven results from the groups, they obtained an average value of 6.0×10^{23} atoms ^{12}C per mole of ^{12}C for Avogadro's number. In addition, from the average mass of a single carbon-12 atom in grams and the definition of the (unified) atomic mass unit (amu), they calculated the conversion factor that relates the amu to the gram as N_A u = 1 g.

Introduction

The International System of Units (the SI unit system) is based on the seven base units: meter, kilogram, second, ampere, kelvin, mole, and candela [1]. These units are defined in terms of a standard chosen by the General Conference on Weights and Measures (CGPM) with permission of the International Union of Pure and Applied Chemistry (IUPAC). The definitions of these units are under constant review and are changed from time to time.

One of these base units is the mole, which is the unit of the amount of a substance. The mole was introduced into the SI unit system by the 14th CGPM in 1971 [1]. It is defined as the amount of substance in a system that contains as many elementary entities as there are atoms in 12.00000 g of carbon-12 [1]. The number of atoms in exactly 12.00000 g of carbon-12 is called Avogadro's number, N_A [2, 3]. If the mass of a single carbon-12 atom in grams is determined, Avogadro's number can easily be calculated by dividing the 12.00000 grams per mole ^{12}C, from the definition of mole, with the mass of a single carbon-12 atom in grams. There are various methods for the determination of Avogadro's number in the literature that are not based on carbon-12 [4–12].

The author asked 37 chemistry teachers, 67 prospective chemistry teachers, 142 freshman science education students, and 142 high school students, as well as several chemistry professors, about the definitions of mole and Avogadro's number. More than half of them defined these concepts as either "Avogadro's number of particles" or "6.022×10^{23}." It is quite obvious that both these answers are incorrect. They were also asked about the origin of Avogadro's number. The results showed that most of them did not know the relationship between Avogadro's number and carbon-12. They thought that Avogadro's number is a constant number assigned as 6.022×10^{23} in order to define the mole. They were also asked why one mole of any substance has a mass in grams that is numerically identical to the mass of a single unit (atom or molecule) in unified atomic mass units (symbol u). None of them could answer this question correctly. In other studies related to the subject, it is reported that chemistry teachers [14] and students [12, 14–17] from various countries, and even some chemistry textbook writers [18], also have the same difficulties. The reason for this may be that they have not studied this concept using an activity based on carbon-12.

In this manuscript we describe an activity in which 52 first-year students in the Department of Science Education, divided into 7 groups, determined the mass of a single carbon-12 atom in grams using mass spectroscopy data and obtained Avogadro's number by dividing the mass of a single carbon-12 atom in grams. Then, using the definition of a mole, they calculated Avogadro's number by dividing 12.00000 g mol^{-1} (carbon-12 mole weight) with this mass. Using the data from the seven groups, they calculated an average value for Avogadro's number. In addition, they calculated the conversion factor that relates the (unified) atomic mass unit to grams by using the definition of the amu and the mass of a single atom of carbon-12 in grams.

Procedure for Evaluating Avogadro's Number

J. J. Thomson determined the ratios of the unit charge to the masses, e/m_e and e/m_p, for the electron and the proton [19]. The first measurement of the charge on the electron, e, was made by R. A. Millikan [19, 20]. The masses of the electron and the proton in grams, m_e and m_p, were calculated from the values of e/m_e and e/m_p and e. The currently accepted values for their rest masses are $9.109\,381\,88(72) \times 10^{-28}$ g and $1.672\,621\,58(13) \times 10^{-24}$ g, respectively [21].

The mass spectrum of methane contains the peaks of $^{1}H^{+}$ and $^{12}C^{+}$ species in addition to those of the other species [22]. The positive ion mass spectrum of methane is shown in

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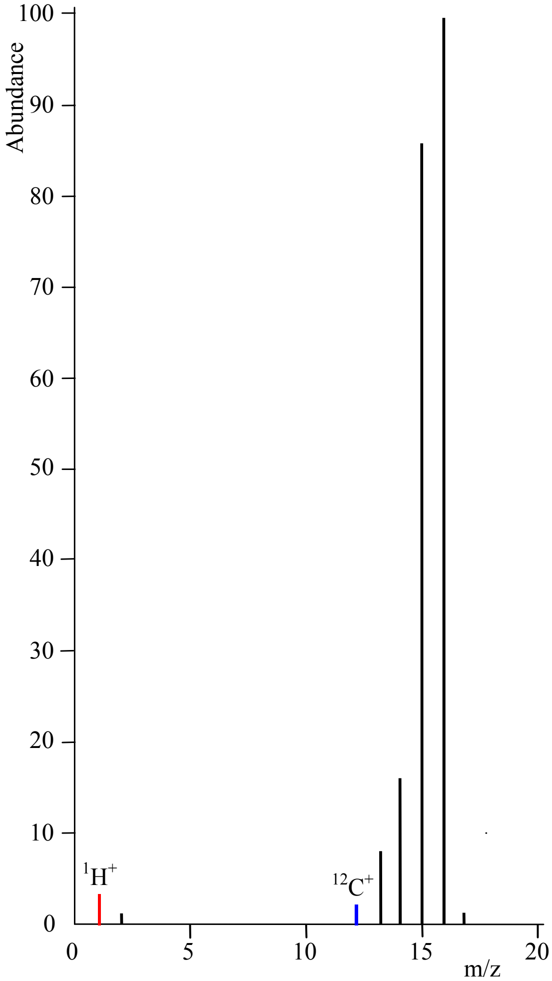

Figure 1. The mass spectrum of methane [22]. This spectrum was enlarged to page size for measurement.

Figure 1. The m/z = 1 and m/z = 12 peaks (red and blue peaks) indicate the presence of $^1H^+$ and $^{12}C^+$ species.

In the mass spectra, although the abscissa axis includes the mass number, this axis is generally related to the mass. There is certainly a mass in grams or kilograms or atomic mass units corresponding to each mass number; therefore, on the condition that x_1 and x_2 are the abscissa lengths of the peaks of the $^1H^+$ and $^{12}C^+$ species, one can write $m_p \propto x_1$ and $m_{^{12}C^+} \propto x_2$, where m_p and $m_{^{12}C^+}$ are the masses of the $^1H^+$ (proton) and $^{12}C^+$ ions. Then, the mass of $^{12}C^+$ ion in grams can be calculated from

$$m_{^{12}C^+} = (x_2 \text{ mm ion}^{-1}\ {}^{12}C^+)\left(\frac{m_p \text{ g ion}^{-1}\ {}^1H^+}{x_1 \text{ mm ion}^{-1}\ {}^1H^+}\right) \quad (1)$$

The mass of a ^{12}C atom is

$$m_{^{12}C} = m_{^{12}C^+} + m_e \quad (2)$$

Thus, according to the definition of a mole, Avogadro's number is

$$N_A = \frac{12.00000 \text{ g mol}^{-1}\ {}^{12}C}{m_{^{12}C} \text{ g atom}^{-1}\ {}^{12}C} \quad (3)$$

In this context, knowing that the standards chosen for the definitions of the mole and the unit of atomic mass are based on the same chemical element is very important. The amu is a standard mass unit that is equal to one-twelfth the mass of a neutral atom of the carbon-12 isotope. According to this definition, the atomic mass of carbon-12 is 12.00000 u. Because the mass of a single carbon-12 atom in atomic mass units (12.00000 u) must be equal to its mass in grams, the factor that relates the amu to the gram can be calculated from

$$m_{^{12}C} \text{ (g atom}^{-1}\ {}^{12}C) = 12.00000 \text{ (u atom}^{-1}\ {}^{12}C) \quad (4)$$

Performance of the Activity

The activity was used in a class of fifty-two first-year students taking a general chemistry course in the Department of Science Education. The students were divided into seven groups. Each group was given a copy of the spectrum shown Figure 1 and asked to measure the abscissa lengths of the peaks of the $^1H^+$ and $^{12}C^+$ species with an ordinary ruler graduated in millimeters. Each group calculated the masses of the $^{12}C^+$ and ^{12}C species and Avogadro's number using eqs 1–3. They obtained a final value of Avogadro's number by calculating the average of all seven values. In addition, they substituted their average value of the mass of a single carbon-12 atom in grams into eq 4 to obtain the conversion factor that relates the amu to gram.

The positive ion mass spectrum of methane in Figure 1 is a reproduced version of the spectrum published elsewhere [22]. For this reproduction, the spectrum was redrawn in its original form by using a common word processor, and then, it was enlarged to fit on a page.

Natural gas contains methane in quite a large proportion and it can be used as the methane source. The mass spectrum of natural gas is quite similar to that of methane [23]. The mass spectrum of methanol also contains the peaks of $^1H^+$ and $^{12}C^+$ ions [24]; therefore, it can be used for the same purpose.

In the performance of the activity, students worked as a cooperative group [25].

Results and Discussion

The students calculated an average value of 6.0×10^{23} atom ^{12}C per mol ^{12}C for Avogadro's number. The results are summarized in Table 1. They also derived the relationship between the amu and gram and found that the amu multiplied by Avogadro's number is equal to one gram (N_A u = 1 g).

The abscissa lengths of the peaks in the spectrum were measured with an ordinary ruler graduated in millimeters. The reliability of the result is highly dependent upon the accuracy of the measurement of the abscissa lengths; however, the purpose of this study was not to determine Avogadro's number with many significant figures, but to make students aware that the definitions of mole and Avogadro's number are based on carbon-12.

Because the definition of a mole is based on a neutral atom of the carbon-12 isotope [1], although it does not change the

Table 1. Results for the Determination of Avogadro's Number

Group	x_1 (mm)	x_2 (mm)	$m_{^{12}C} \times 10^{+23}$ (g)	N_A (10^{23} mol^{-1})
1	4.1	48.8	2.0	6.0
2	4.1	48.8	2.0	6.0
3	4.1	49.0	2.0	6.0
4	4.1	48.6	2.0	6.0
5	4.1	48.8	2.0	6.0
6	4.1	48.8	2.0	6.0
7	4.1	48.8	2.0	6.0
Average			2.0	6.0

result, formally, the mass of an electron should be added to the mass of the $^{12}C^+$ ion.

The standards chosen for the definitions of the mole and the unit of atomic mass are based on the same chemical element. Since 1971, the number of atoms in 12.00000 g of carbon-12 has arbitrarily been assigned as the standard for the mole [1]. Since 1961, one-twelfth of the mass of a single carbon-12 atom has arbitrarily been assigned as the standard for the unit of atomic mass [1]. If the standards are changed, the values of Avogadro's number and atomic masses will also change. For example, according to the base of J. J. Berzelius' atomic mass scale, an atomic mass unit is one-hundredth of the mass of a single oxygen atom [3]. According to this scale, the mole and Avogadro's number may be defined as "the amount of substance of a system that contains as many elementary entities as there are atoms in 100 g of oxygen" and "the number of atoms in exactly 100 gram of oxygen," respectively. Then, the value of Avogadro's number would be 3.77×10^{24} atoms O per mole O.

In summary, the size of Avogadro's number is dependent on the standard chosen for the definition of the mole. In fact, we cannot accurately know the value of Avogadro's number because it is such a large number that measuring devices are not sufficient for this purpose. In terms of the basis of 12.00000 g carbon-12, Avogadro's number is a number with 24 digits, but its current value has only nine significant digits [$6.022\ 141\ 99(47) \times 10^{23}$] [21]. In the future, scientists may determine more than these nine digits.

The following points should be taken into consideration in the presentation of the mole and Avogadro's number in textbooks and classrooms:

(a) The relationship between the mole and the SI unit system should be presented.

(b) The relationship between the standards chosen for the definitions of the mole and the atomic mass unit should be explained.

(c) An activity relating to the determination of Avogadro's number, which is in accordance with its definition, should be carried out.

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