Exothermic Bond Breaking: A Persistent Misconception

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The chemical bond remains the most distinctive feature of chemistry. Formed as the result of an attraction between the participating atoms, it requires an input of energy to separate the atoms or break the bond. However, an alarming fraction of science students in their second and higher university years seem to adhere to the belief that energy is obtained when chemical bonds are broken. Discussions with many students, as well as responses provided on exams, reveal that the students are often misinformed or provided with conflicting information at the high-school, junior-college, and even university levels, as to the nature of ATP hydrolysis and, very often as a result, about bond breaking and making in general.

Understanding the Misconceptions

To provide a more quantitative measure of students' knowledge in this area I have asked over 600 primarily biochemistry and physiology students over the past several years to respond to a questionnaire at the onset of a course in introductory physical chemistry. The students involved were divided between those having spent the previous year as university freshmen and those entering from a two-year junior-college program. In either case the students would have completed a general chemistry course, with many having taken or concurrently taking, an organic chemistry course as well as a course in biology at the cell and molecular level.

The vast majority of these students had heard of ATP and the term "high-energy phosphate" and were aware that the conversion of ATP to ADP is an exothermic process. On the other hand as the summary in Table 1 reveals, fewer than 7% of the students realized that the O−P bond is a relatively weak bond that requires an input of energy to break. More than 40% of the students mistakenly felt that the "high-energy phosphate" bond was a particularly *stable bond* and a significant quantity of energy *was released* when it was broken. Even more surprisingly, more than 85% of the students selected an incorrect response (see response C in Table 1), either alone or as part of a combination that stated that bond breaking is exothermic.

The belief that the rupturing of bonds in general is exothermic is emphasized in the responses to a second question appearing in Table 2. Over 80% of the students selected bond breaking in the reactants as the origin of the energy release in a simple combustion reaction. In the most recent survey involving 75 students it was found that results were unchanged when the order of the combustion and ATP questions was reversed.

Table 1. Survey of Student Knowledge on the Energetics of Bond Making and Breaking Associated with ATP Hydrolysis

Choices	Student (%)
A and C	40.8
B and C	19.7
C only	26.3
B only	5.30
B and D	6.60
Don't know	1.30

NOTE: Students were asked to select from responses A–D to complete the following sentence: An O−P bond in ATP is referred to as a "high-energy phosphate bond" because: A. The bond is a particularly stable bond.; B. The bond is a relatively weak bond.; C. Breaking the bond releases a significant quantity of energy.; D. A relatively small quantity of energy is required to break the bond.

Table 2. A General Question in the Survey of Student Knowledge on the Energetics of Bond Making and Breaking

Phrase	Students (%)
1. Breaking the C=C bond	32.9
2. Breaking the C−H bonds	3.90
3. Beaking the O=O bonds	2.40
4. All of the above	40.8
5. Forming the C=O and O−H bonds	20.0

NOTE: Students selecting an appropriate phrase (1–5) to complete the sentence: The release of energy (exothermic) during the combustion of ethylene, $CH_2{=}CH_2(g) + 3O_2(g) \rightarrow 2CO_2(g) + 2H_2O(g)$, is due to:

Resolution of the Misconception

Students are provided with the correct responses to the questionnaire and these are contrasted with the doctrine of "liberating energy on bond breaking". This is done with a review of the fundamental nature of a chemical bond illustrated with the aid of a potential energy diagram of the type shown in Figure 1. Employing hydrolysis and simple combustion reactions as examples the apparent conflict is resolved

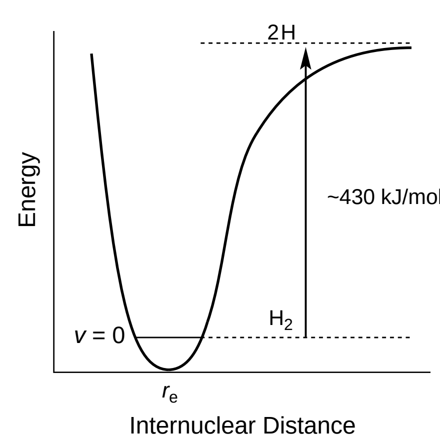

Figure 1. An electronic energy diagram for H_2, a typical diatomic molecule. The large input of energy required to separate the atoms, or break the bond, is emphasized. The zero-point vibrational level is identified as $v = 0$.

with a consideration of the overall energy balance of the bond rupture and formation associated with most reactions. The exothermic nature of the hydrolysis of ATP is presented in the simple manner illustrated in Figure 2. It is emphasized that the high-energy O−P bond in ATP along with an O−H bond in a water molecule both require a significant input of energy to break, and it is only the subsequent formation of the bonds in the products that results in an energy decrease and thus the release of energy. It is stressed that while the same number of bonds are broken and formed in reactants and products, respectively, the energy balance from these processes is negative as result of the formation of the stronger bonds in the products. Following this consideration of the energetics of bonding, the students are asked at a subsequent lecture to respond to a second questionnaire to ascertain their opinions as to the source of the misconceptions and confusion. A sample of this questionnaire with typical responses appears in Table 3.

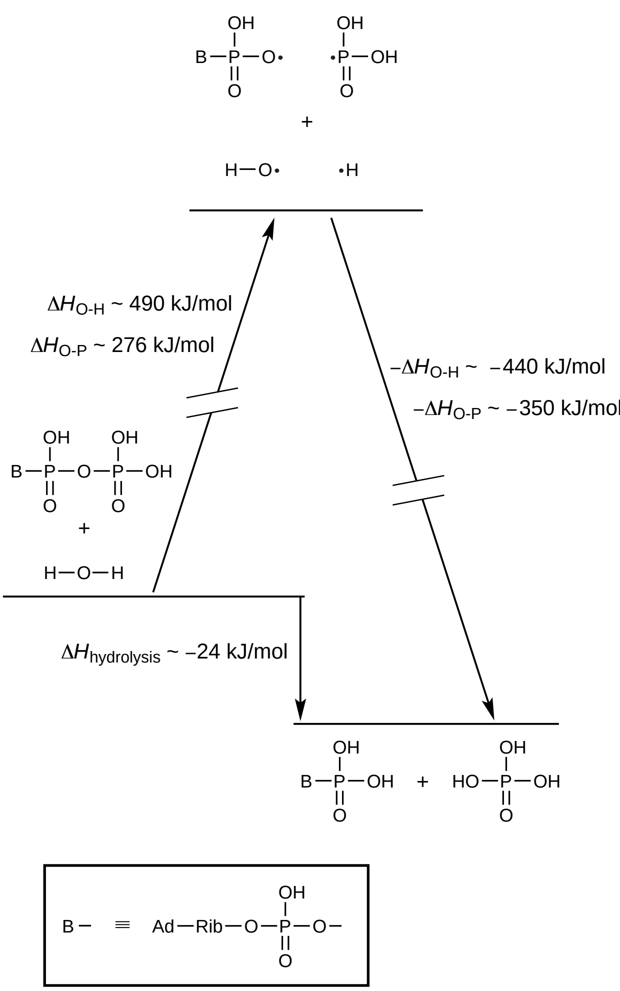

Figure 2. The ΔH of hydrolysis of ATP ($\Delta H_{hydrolysis}$) is depicted in terms of approximate bond enthalpies ($\Delta H_{x\text{–}x}$) for the reactants and products. With reactants and products in their non-ionized forms the exothermic nature of the reaction is seen as a balance of bond breaking and making.

Sources of the Misconception

The results of this second survey reveal that students identify primarily high-school and junior-college level biology as providing an incorrect picture of the energetics of bond rupture and formation and of the ATP-to-ADP conversion in particular. Students, however, felt that it was not only in their biology courses where they had received misinformation. The responses from the survey indicated that 40% of the students were of the opinion that in their high school, junior college and even university chemistry instruction they had been told that bond breaking was exothermic. These responses were generally consistent with the feedback I have gotten over the years from individual students on the information they receive, including that from within this institution.

The concept of energy changes in reactions arising as a balance of bond breaking and bond making appears in the modern chemistry texts *(1)* these students would have used in their general chemistry courses. However, general chemistry courses introduce students to a broad range of topics in chemistry, so that most students do not appear sufficiently confident to recognize misinformation in any one area when they encounter it elsewhere. Terms such as the “high-energy phosphate bond”, and statements such as “in the conversion of ATP to ADP a phosphate group is *cleaved off* resulting in a release of energy” *(2)* are easily misinterpreted. The description below of the phenomenon excerpted from a high-school biology text *(2)*, illustrates how brevity, in this case by not including the water as a reactant, can be misleading:

> To release energy, a phosphate group (P) breaks off the ATP leaving adenosine diphosphate (ADP), a molecule that has only two phosphate groups. The following equation summarizes the reaction:
>
> $$\text{ATP} \rightleftharpoons \text{ADP} + \text{P} + \text{Energy}$$

In other cases incorrect statements, such as “energy trapped in the *high-energy phosphate bond* is liberated when the bond is broken” *(3)* or that the bond releases energy when it is broken *(4, 5)*, lead to misconceptions in the minds of instructors as well as those of the students. The term “energy stored in chemical bonds” widely used in chemistry texts *(6)*, is also easily misconstrued, in particular when encountered in the background of the confusion centered around the ATP complication. From student comments on the second questionnaire two clarify the sources of confusion, as paraphrased below:

- Biology teachers tend to oversimplify chemical reactions to make the biology easier, but it makes everything more confusing in the end.
- The teacher in our biology course (junior-college level) stated that the ATP to ADP conversion did involve a more complicated reaction, but I still left assuming that energy was released as a result of bond breaking.

I should add that there are recent introductory biology texts *(7)*, in addition to the more specialized publications that students can be referred to *(8–11)*, which not only provide a more detailed and correct interpretation of the energetics of the ATP to ADP conversion, but also draw attention to the potential for confusion.

Table 3. Bioenergetic Survey II[a]

Question	Response	Students (%)
1. Prior to the first survey you thought that breaking the "high-energy phosphate bond" resulted in the release of energy.	True	72.0
	Uncertain	16.0
	Untrue	12.0
2. Prior to the 1st survey you thought that breaking bonds in general resulted in the release of energy.	True	44.0
	Uncertain	9.3
	Confused, due to ATP example	21.4
	Untrue	25.3
3. The correct picture of the energy changes associated with bond breaking and making, in general, was provided to you in (select more than 1 if applicable):	HS chem[b]	24.0
	HS biology	5.3
	Jcoll chem	29.3
	Jcoll biology	6.7
	Univ biology	5.3
	Univ chem	52.0
	Nowhere	12.0
4. An incorrect picture of the energy changes associated with bond breaking and making, in general, was provided to you in (select more than 1 if applicable):	HS chem	36.0
	HS biology	29.3
	Jcoll chem	22.7
	Jcoll biology	29.3
	Univ biology	25.3
	Univ chem	6.7
	Nowhere	12.0
5. The correct picture of the energy changes associated with ATP hydrolysis was provided to you in (select more than 1 if applicable):	HS biology	2.7
	Jcoll biology	8.0
	Jcoll chem	10.7
	Univ biology or biochem	9.3
	Univ chem	70.7
6. An incorrect picture of the energy changes associated with ATP hydrolysis was provided to you in (select more than 1 if applicable):	HS biology	37.7
	Jcoll biology	39.1
	Jcoll chem	8.7
	Univ biology or biochem	27.5
	Univ chem	2.9

[a]Student opinion on the information on the energetics of bonding obtained in earlier courses, 2000, $N = 76$.

[b]HS–high school; Jcoll–junior college (equivalent to HS grade 12 plus freshman year); Univ–university.

Summary

If students are alerted to the confusion and misinformation about bond making and bond breaking that they were likely exposed to, coupled with a review of the correct picture of bond rupture and formation, the problem is largely resolved. Students then recognize the misconceptions that they encounter.

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