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Ions and ionisation energy

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Abstract

Previous research (Taber, 1999, 2000a) has shown that A-level students in the United Kingdom had difficulty understanding the concepts involved in ionisation energy. The purpose of this study, which involved the use of interviews and written instruments, was to determine if Grades 11 and 12 students (16 to 19 years old) in Singapore had similar alternative conceptions and explanatory principles of the factors influencing ionisation energy as their A-level counterparts in the United Kingdom (U.K.), as well as to explore students’ conceptions of the trend of ionisation energy across different elements in the Periodic Table. The results showed that many students in Singapore applied the same octet rule framework and conservation of force thinking to explain the factors influencing ionisation energy as students in the U.K. In addition, the students resorted to relation-based reasoning to explain the trend of ionisation energy across period 3 elements. The authors believed that the way ionisation energy was taught and presented in textbooks could be the cause of students’ difficulties in understanding ionisation energy. Teachers and textbooks need to focus explicitly on the effects of nuclear charge, the distance of the electron from the nucleus, the repulsion/screening effect of the other electrons present, and the interplay between these factors to explain the factors influencing ionisation energy and the trend in ionisation energy across period 3.

Introduction

Science instruction, from the elementary school to the university level, is frequently disappointing as far as promoting students’ understanding of science is concerned. Students are often in full command of science terminology and, for example, might be able to provide the names of animals and plants, to write down the Schroedinger equation without any difficulties, or to provide key examples when presented with formulas. However, there very often is no deep understanding behind the facade of knowledge. (Duit & Treagust, 1995, p. 46).

Many researchers agree that the most important things that students bring to class are their conceptions (Driver & Oldham, 1986; Osborne & Wittrock, 1985). Duit and Treagust (1995) define conceptions as “the individual’s idiosyncratic mental representations” while concepts are “something firmly defined or widely accepted” (p. 47). Children develop ideas and beliefs about the natural world through their everyday life experiences. These include sensual experiences, language experiences, cultural background, peer groups, mass media as well as formal instruction (Duit & Treagust, 1995). Some of these ideas and beliefs, such as those about light and sight (Driver, 1995) may be similar across cultures as children have very similar personal experience with phenomena.

Students’ existing ideas are often strongly held, resistant to traditional teaching and form coherent though mistaken conceptual structures (Driver & Easley, 1978). Students may undergo instruction in a particular science topic, do reasonably well in a test on the topic, and yet, do not change their original ideas pertaining to the topic even if these ideas are in conflict with the scientific concepts they were taught (Fetherstonhaugh & Treagust, 1992). Duit and Treagust (1995) attribute this to students being satisfied with their own conceptions and therefore seeing little value in the new concepts. Another reason they proposed was that students look at the new learning material “through the lenses of their preinstructional conceptions” (p.47) and may find it incomprehensible. Osborne, Bell and Gilbert (1983) state that students often misinterpret, modify or reject scientific viewpoints based upon the way they really think about how and why things behave, so it is not surprising that research shows that students may persist almost totally with their existing views (Treagust, Duit, & Fraser, 1996). When the students’ existing knowledge prevails, the science concepts are rejected or there may be misinterpretation of the science concepts to fit even support their existing knowledge. If the science concepts are accepted, it may be that they are accepted as special cases, exceptions to the rule (Hashweh, 1986), or in isolation from the students’ existing knowledge, only to be used in the science classroom (Osborne & Wittrock, 1985; de Posada, 1997) and regurgitated during examinations. Additional years of study can result in students acquiring more technical language but still leave the alternative conceptions unchanged (de Posada, 1997).

Chemistry is a difficult subject for most students because it involves “abstract and formal explanations of invisible interactions between particles at a molecular level” (Carr, 1984, p.97). Studies have shown that students have alternative conceptions in many chemistry topics (e.g. Garnett, Garnett, & Hackling, 1995; Nakhleh, 1992). In the topic of ionisation energy, Taber (1999, 2000a) found that students had alternative conceptions of the principles determining the magnitude of ionisation energy because they based their explanations on the octet rule/full shell framework – atoms try to gain full outermost shells or octets of electrons in the outermost shell, and only give them up, if at all, under extreme circumstances. He also argues that the students did not or could not apply basic
electrostatic principles that they learned in physics to explain the interactions between the nucleus and electrons in an atom. In addition, students also adopted an alternative explanatory principle, the 'conservation of force' conception, that is, that a charged body gives rise to a certain amount of force which is available to be shared amongst oppositely charged bodies. They thought that an atom's electrons shared-out the attraction from its nuclear charge, so successive ionisations resulted in a greater share of the nuclear charge acting on each of the remaining electrons, resulting in increasing successive ionisation energies.

This paper describes a study undertaken in Singapore to determine if Grade 11 and 12 students (16 to 19 years old) had similar alternative conceptions and explanatory principles of the factors influencing ionisation energy as their A-level counterparts in the United Kingdom, as well as to explore students' conceptions of the trend of ionisation energy across different elements in the Periodic Table. The extension of Taber's study to also include students' conceptions of the trend of ionisation energy was in line with requirements of the A-level chemistry syllabus on ionisation energy. In Singapore, students spend about 90 minutes of lectures on ionisation energy, during which the teacher would attend to the factors influencing ionisation energy, the trend of successive ionisation energies of an atom, and the trends of ionisation energy down a group and across Period 3. Students also spend about 45 to 90 minutes solving ionisation energy problems in class. They usually encounter ionisation energy again when they learn Hess' Law in energetics and carry out calculations involving energy cycles. Teachers would also review the trend of ionisation energy with proton number across the third period when they cover chemical periodicity in inorganic chemistry. It has to be noted that the A-level chemistry does not include quantum mechanics, so no quantum mechanical explanations were used in Taber's study as well as in this study.

Methodology
This study adopted the methodology outlined by Treagust (1995). The content framework of A-level ionisation energy was defined by a list of propositional knowledge statements,* a concept map (Figure 1) and a matching of the propositional knowledge statements to the concept map to ensure internal consistency. The propositional knowledge statements were either adapted from Taber's (1997) work or identified from the A-level syllabus and two A-level textbooks. The concept map was drawn by the first-named author based on the propositional knowledge statements, the A-level syllabus, and the two A-level textbooks. A justification multiple choice instrument (see Appendix A) was developed and administered to 130 Grade 12 students from three schools. Eleven Grade 12 students who took the test were interviewed using the instrument as the interview protocol, to determine whether any item was ambiguous and to probe the reasons for their answers.

* A list of propositional knowledge statements is available from the first author.

Results and Discussion
Students' conceptions of ionisation energy are discussed under the sections: octet rule framework, conservation of force thinking, and relational based thinking (Driver et al., 1996).

Octet rule framework
When ionisation energy is supplied to a sodium atom, the valence electron is removed and the sodium ion (Na⁺) is formed. The sodium ion, however, can attract an electron to reform the sodium atom, releasing energy in the process. Thirty-nine students (30%) indicated in item 2 that a sodium ion would not combine with an electron to reform the sodium atom, with 21 students giving reasons to the effect that the sodium ion is already in a stable octet configuration and will not want to gain an electron to form the relatively unstable sodium atom. In item 4, 101 students (78%) indicated that the gaseous sodium ion is more stable than the gaseous sodium atom, with 85 students stating to the effect that the sodium ion had an octet/noble gas/full valence shell configuration so it was more stable than the sodium atom. Students also gave similar reasons during interviews, as illustrated below:

I: Why do you say it's more stable?  
S17: Because Na⁺ has...
S16: Octet structure.
S17: Yes...we learn that if it is completely filled, it's more stable.  

I denotes the interviewer; S16 & S17 denote students 16 & 17.

The findings above reflect the results obtained by Taber (1999) who found that 53 out of 110 A-level students (16 to 19 years old) believed that the "sodium atom would not be considered as stable as it does not have a full outer shell" (p. 101). He also found that a third of the students indicated that only one electron could be removed from the sodium atom as it then had a stable configuration. This was despite the fact that the students had studied patterns in successive ionisation energy. Taber (1997, 1999, 2000a) further investigated the octet rule framework by asking different groups of students which they thought was the more stable species, the sodium anion (Na⁻) or the sodium atom. The majority of the students responded that the sodium anion was more stable than the atom — a result later replicated, and extended to other examples such as the ions C⁶⁺ and C⁴⁻ which were judged more stable than a neutral carbon atom (Taber, 2002a). A significant minority of post-graduate trainee science teachers in the U.K. (Taber, 2000b) also believed that the anion (Na⁻) was more stable than the neutral atom. Thus, the octet rule framework seemed to be common among students and even among trainee-teachers. The authors believed that the octet rule framework was carried over from the learning of bonding in Grade 9 and 10 chemistry (14 to 17 years old) — for example, it was common to hear teachers say that 'the sodium atom needed to lose an electron to achieve a stable octet electronic configuration'. Taber (2003) believes that the octet rule framework has internal coherence "because it comprises a range of ideas that are mutually self-
The diagram illustrates the concept map of ionisation energy. It outlines the relationship between electrons, nuclei, and energy levels, focusing on the electron configuration and ionisation energy (IE) across different energy shells. The key points include:

- **Electrons**: Fills up from the lowest energy orbital upwards (s,p,d,f).
- **Orbitals**: Occupies orbitals within the same subshell singly with parallel spin before pairing up with opposite spin.
- **Energy Level**: Fills up from the lowest energy shell onwards.
- **Removal of Electron**: Requires energy to remove an electron from an isolated gaseous atom/ion.
- **Nuclear Charge**: Linked to the energy required for removal of an electron.
- **Screening Effect**: Greater screening effects lead to decreasing IE due to distance.
- **Periodic Trend**: The trend of IE across a period is increasing, except for positively charged particles.
- **Group Determination**: Mg/Al & P/S in period 3 can determine the group, which the element belongs to.

The diagram provides a visual representation of these concepts, linking each element with its corresponding energy level, electronic configuration, and ionisation energy. The key highlights the relationship between the number of protons (p), neutrons, and electrons (e), and how these factors influence the ionisation energy.
supporting” (p. 102). This is further elaborated in the next section.

**Fully-filled and half-filled sub-shells**

An alternative conception that is related to the octet rule framework is that species with fully-filled or half-filled sub-shells are more stable than those without such electronic configurations. For example, in item 6, 11 students indicated that the first ionisation energy of magnesium was greater than that of sodium because magnesium has a stable fully-filled 3s sub-shell. The reason for the higher first ionisation energy of magnesium is that the increase in nuclear charge in the magnesium atom (12 protons in magnesium compared to 11 in sodium) outweighs the repulsion between the two electrons in the 3s orbital. However, these students seemed to believe that the higher ionisation energy was solely due to stability resulting from the filling of the 3s sub-shell; to disrupt the ‘stable’ filled 3s sub-shell configuration would require additional energy. Six students invoked the same reasoning to explain why the first ionisation energy of magnesium was higher than that of aluminium in item 7. The students did not realize that in this case, the diffuse character of the 3p orbital overweighs the increase in nuclear charge of aluminium compared to magnesium resulting in the lower first ionisation energy of aluminium.

A number of students exhibited ‘stable half-filled sub-shell’ thinking in items 9, 10 and 11. For example, 12 students in item 9 and 5 students in item 10 stated that phosphorus has a higher first ionisation energy than silicon and sulfur, respectively, because the 3p sub-shell of phosphorus was half-filled, hence more stable. They did not consider the higher nuclear charge of phosphorus compared to silicon, or the effect of the repulsion of paired electrons in one of the 3p orbitals of sulfur. This is illustrated by the following extract of an interview:

S1?: I think silicon and phosphorus I will agree that the IE (ionisation energy) for silicon is lower...in other words the IE for phosphorus is higher because if you remove electrons from the 3p\(^1\) you are disturbing the...I think first you are disturbing the stable structure of the half-filled (sub-shell)...

It is not surprising that students had the alternative conception that a fully-filled 3s sub-shell and half-filled 3p sub-shell gave magnesium and phosphorus extra stability, respectively. Firstly, the ‘stable fully-filled or half-filled sub-shell’ thinking is a ‘logical’ extension of the octet rule framework, thus supporting it. Furthermore, teachers often use this as a rule-of-thumb to ‘explain’ the anomaly in the ionisation energy trend across periods 2 and 3 of the Periodic Table, and to help students remember the anomaly. A textbook on introductory tertiary chemistry (Lee, 1977) also used the octet rule framework and stable half-filled and fully-filled sub-shells to ‘explain’ the anomaly.

“The values for Ne and Ar are the highest in their periods because it requires a great deal of energy to break a stable filled shell of electrons*”. There are several irregularities. The high values for Be and Mg are attributed to the stability of a filled s shell. The high values of N and P indicate that a half-filled p level is also particularly stable. The values for B and Al are lower because removal of one electron leaves a stable filled s shell, and similarly with O and S a stable half-filled p shell is left”

(Lee, 1977, p.96)

*Cann (2000) also commented that this “half-filled (and also completely filled) shells having intrinsic stability” reason was common and could be found in textbooks, but it offered “no explanation in terms of electrostatic or quantum mechanical interactions within the atom” (p. 1056).

Thus, the “stable half-filled and fully-filled sub-shell” thinking is very attractive to students and easily adopted by them because it seems to be a ‘logical’ extension of the octet rule framework and because they learned it during lessons or read it in textbooks.

**Conservation of force thinking**

In item 3, 79 students (61%) agreed with the statement that the attraction of the nucleus for the ‘lost’ electron would be redistributed among the remaining electrons in the sodium ion. This result is similar to that obtained by Taber (1999). A reason given by 29 of them was that since the same number of protons was attracting one less electron, the remaining electrons in the sodium ion would experience a greater attraction from the nucleus. An extract of an interview illustrating the conservation of force thinking is given below:

S4: Because the number of protons remain the same but the number of electrons has decreased...so it’s like there is a greater charge, a greater positive charge...attracting a less...I mean a smaller negative charge...so it would attract it even closer.

I: Yes...

S4: Yes it would attract it even closer so it...it redistribute like...the total amount of...positive charge will attract the total amount of negative charge left after one electron has been removed.

The outermost electron of sodium is in the third shell which is shielded/screened from the nucleus by two electrons in the first shell and eight electrons in the second shell. The next electron to be removed comes from an inner shell which is closer to nucleus and experiences shielding/screening from only two electrons in the first shell. Hence the second ionisation energy of sodium is higher than the first because the second electron is more strongly attracted to the nucleus as it is nearer to the nucleus and experiences less shielding than the first electron; it is not higher because the attraction of the nucleus for the ‘lost’ electron would be redistributed among the remaining electrons in the sodium ion.

In item 5, 21 students who agreed that the second ionisation energy of sodium was greater than the first, gave the reason that force of attraction per electron has increased with the...
earlier loss of an electron. Thus, in addition to the octet rule framework, students also use the conservation of force thinking to explain, in item 5, why the second ionisation energy of sodium is greater than the first.

Relation-based reasoning
Factors influencing ionisation energy include the nuclear charge, the distance of the electron from the nucleus and the repulsion and shielding/screening effect of the other electrons present. The results from items on the trend of the first ionisation energy across period 3 showed that students did not consider all the three factors but based their reasons exclusively on one or two factors. Driver et al. (1996) describe this type of thinking as relation-based reasoning, where “students tend to consider only one factor as possibly influencing the situation – the one which they see as the ‘cause’. As a consequence, other possible influential factors are overlooked” (p. 115). For example, in item 6, 29 students stated that the first ionisation energy of sodium was greater than magnesium because the 3s electrons in magnesium were paired up and experience inter-electronic repulsion – this was opposite to the stable fully-filled sub-shell conception. It is true that there will be repulsion between the 3s electrons of magnesium, but in this situation, the effect of an increase in nuclear charge in magnesium outweighs the repulsion between the two 3s electrons. In addition, the spherical nature of the 3s orbital also allows the electrons to penetrate the screening effect of the inner shell electrons.

Many students also neglected the effect of nuclear charge when they gave the reason for ionisation energy decreasing across a period. These students believed that the more electrons an atom has, the further away the electrons are from the nucleus, or the greater the repulsion between the electrons. For example, 34 students stated in item 8 that sodium had a higher first ionisation energy than aluminium because the 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium. Two students stated during interviews that they had this impression because of the filling of the orbital diagram of aluminium – they thought that putting an arrow in the first 3p box for aluminium indicated that the electron in the box was further away from the nucleus compared to the 3s electron of sodium. They did not realize that the orbital diagrams describe the relative energy levels of electrons of an atom; the diagrams cannot be used to compare distances of electrons from the nucleus of different atoms.

Implications
The results from the administration of the justification multiple choice instrument on ionisation energy and the interviews with students agree with many of the research findings on ionisation energy by Taber (1999, 2000a) in the United Kingdom. It seems that the A-level students in Singapore and the United Kingdom had very similar alternative conceptions, probably because they study similar content. The study also highlighted another area of student difficulty in ionisation energy, that is, the anomaly in the trend of ionisation energy across period 3. Since the students would hardly have encountered the concepts on ionisation energy in everyday life, it was likely that the alternative conceptions arose from the way ionisation energy was taught and learnt. As mentioned earlier in the paper, a textbook and A-level teachers also used the ‘stable fully-filled s sub-shell’ and ‘stable half-filled p sub-shell’ heuristics to explain, for example, why magnesium has a higher first ionisation energy than aluminium and why phosphorus has a higher first ionisation energy than sulfur. Since the octet rule framework did not conflict with the ‘stable fully-filled and half-filled sub-shell’ explanations, the ‘stable fully-filled and half-filled sub-shells’ explanation is readily accepted by students. Taber (2003) believes that some alternative conceptions in chemistry derive from “teaching that has attempted to avoid or ignore the more abstract aspects of the subject” (p. 106). Thus, the use of heuristics in the teaching of bonding and ionisation energy could be the most likely cause of the octet rule framework and the related ‘stable filled and half-filled sub-shell’ explanations. The conservation of force thinking could have arisen because the students did not integrate the knowledge of electrostatics learned in physics with the concepts of ionisation energy learned in chemistry (Taber, 1998). Several students in the Singapore sample did not do physics at A-level, so they did not have the required knowledge of electrostatics at all!

Thus, the teacher has to review or introduce basic electrostatics during the introduction to ionisation energy. The teacher also needs to focus explicitly on the effects of nuclear charge, the distance of the electron from the nucleus and the repulsion/screening effect of the other electrons present, and the interplay between these factors, to explain the factors influencing ionisation energy and the trend in ionisation energy across period 3. The concept map (Figure 1) and list of propositional knowledge statements can be used to make explicit what exactly is required to learn ionisation energy, and help teachers not to overlook important concepts during their teaching (Tan, 2002). In addition, the teacher needs to point out any misleading material in textbooks that presents heuristics as explanations for anomalies in the trend of ionisation energy across a period. This could minimise the acquisition of the various alternative conceptions discussed in the paper, as well as students’ use of relational thinking where they only concentrate on one factor and ignore the rest.

Taber (2002b) proposes that students be taught the concept of core charges which be applied to explain ionisation energy, as well as electronegativity, bond polarity, bond fission and atomic size. Core charge, i.e. nuclear charge minus number of shielding electrons, is a useful concept at this level of study (where a simple approximation that electrons in inner shells shield electrons in outer shells). When the concept of core charge is understood by students, then it is possible to model explanations of ionization energy where there are only two major factors: core charge, and electron-nucleus distance. At present such recommendations are largely based on considerations of the conceptual structure of the subject, general knowledge about the nature of learning, and the specific results of
research into student thinking. Studies of student conceptions provide starting points, and learning theory suggests where teaching and learning can go wrong. When these factors are considered alongside analyses of the curriculum content (e.g. propositional knowledge statements and Figure 1) it is possible to propose change in teaching practice. It would be useful for future research to explore how student learning outcomes (as discussed in the present paper) might be related to the style and content of teacher presentations (for example, following the recommendations that arise from research such as the present study): however, the authors recognise the methodological difficulties inherent in such research.

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References


Appendix A
Examples of items in the justification multiple choice instrument

Sodium atoms are ionised to form sodium ions as follows:

Na(g) → Na+(g) + e

2. Once the outermost electron is removed from the sodium atom forming the sodium ion (Na+), the sodium ion will not combine with an electron to reform the sodium atom.

A True.
B False.
C I do not know the answer. ( )

Reason:

3. When an electron is removed from the sodium atom, the attraction of the nucleus for the ‘lost’ electron will be redistributed among the remaining electrons in the sodium ion (Na+).

A True.
B False.
C I do not know the answer. ( )

Reason:

6. Sodium, magnesium and aluminium are in Period 3. How would you expect the first ionisation energy of sodium (1s2 2s2 2p6 3s2) to compare to that of magnesium (1s2 2s2 2p6 3s2)?

A. The first ionisation energy of sodium is greater than that of magnesium.

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