Educational Research

The ionisation energy diagnostic instrument: a two-tier multiple-choice instrument to determine high school students' understanding of ionisation energy

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Abstract: The topic of ionisation energy is important as the concepts involved provide the foundation for the understanding of atomic structure, periodic trends and energetics of reactions. Previous research has shown that A-level (high school) students in the United Kingdom had difficulty understanding the concepts involved in ionisation energy. This paper describes the development and administration of a two-tier, multiple-choice instrument on ionisation energy, the Ionisation Energy Diagnostic Instrument, to determine if A-level students (Grade 11 and 12, 17 to 18 years old) in Singapore have similar alternative conceptions to those of their counterparts in the United Kingdom, as well as explore their understanding of the trend of ionisation energies across Period 3. The items in such instruments are specifically designed to identify alternative conceptions and misunderstandings in a limited and clearly defined content area. The results showed that students in Singapore applied the same octet rule framework and conservation of force thinking to explain the factors influencing ionisation energy as the students in the United Kingdom. In addition to the above alternative frameworks, many students in Singapore also resorted to relation-based reasoning to explain the trend of ionisation energies across Period 3 elements. [*Chem. Educ. Res. Pract.*, 2005, **6** (4), 180-197]

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Introduction

Many researchers agree that the most important significant things that students bring to class are their conceptions (Ausubel, 1968, 2000; Driver et al., 1986). 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 et al., 1995). Studies have revealed that students bring with them to science lessons certain ideas, notions and explanations of natural phenomena that are inconsistent with the ideas accepted by the scientific community (Osborne et al., 1983). These existing ideas are often strongly held, resistant to traditional teaching and form coherent though mistaken conceptual structures (Driver et al., 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 et al., 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 et al. (1983) state that students often misinterpret, modify or reject scientific viewpoints on the basis of 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 et al., 1996). In this paper, the term 'alternative conceptions' is used to describe student conceptions that differ from scientific concepts. The authors agree with Wandersee, Mintzes and Novak (1994) that the term "*confers intellectual respect on the learner who holds those ideas – because it implies that alternative conceptions are contextually valid and rational and can lead to even more fruitful conceptions (e.g., scientific conceptions)*" (p. 178).

Thus, students' alternative conceptions have to be identified so that measures can be taken to help students replace them with (or develop them into) more scientifically acceptable concepts (Taber, 1998a). Studies in which students' alternative conceptions are described cover a wide range of subject areas including chemistry (Garnett et al., 1995; Barker et al., 2000; Pedrosa et al., 2000; Schmidt, 2000; Taber et al., 2000; Taber, 2001; De Jong et al., 2002; Harrison et al., 2002). A useful review of alternative conceptions at secondary school level was provided by Driver et al. (1994). Besides exploring and identifying students' alternative conceptions, most of these studies provide implications for the teaching and learning of the concepts examined.

Methods used to determine students' understanding of concepts include concept mapping (Novak, 1996), interviews (Carr, 1996) and multiple-choice diagnostic instruments (Treagust, 1995). In this study, a two-tier multiple-choice instrument (Treagust, 1995) was developed and used to determine students' understanding of the concepts involved in ionisation energy. The items in two-tier multiple-choice diagnostic instruments are specifically designed to identify alternative conceptions and misunderstandings in a limited and clearly defined content area. The first part of each item consists of a multiple-choice content question having usually two or three choices. The second part of each item contains a set of four or five possible reasons for the answer to the first part; this makes the diagnostic instrument more powerful and effective as it allows an insight to the underlying reasons for the student's answer. Incorrect reasons (distracters) are derived from actual student alternative conceptions gathered from the literature, interviews and free response tests. This methodology has been used to develop diagnostic tests in chemistry, for example, on covalent bonding (Peterson et al., 1989), chemical bonding (Tan et al., 1999), chemical equilibrium (Tyson et al., 1999), and qualitative analysis (Tan et al., 2002).

The topic of ionisation energy has traditionally formed part of the A-level chemistry curriculum studies in many parts of the world, including Singapore and the UK. The topic is important as the concepts involved also provide the foundation for the understanding of atomic structure, periodic trends and energetics of reactions (Taber, 2003a). However, it is a difficult topic to learn because it involves "*abstract and formal explanations of invisible interactions between particles at a molecular level*" (Carr, 1984, p. 97). For example, Taber (1998a,b, 1999, 2003a) found that students had difficulty in understanding the principles determining the magnitude of ionisation energy. This is because students based their explanations on the octet rule/full shell framework and 'conservation of force' conception, and 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.

Purpose

The study sought to develop a two-tier multiple-choice diagnostic instrument to determine if A-level students in Singapore 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 energies across different elements in the Periodic Table. This extension of Taber's (1999) study to include students' conceptions of the trend of ionisation energies was in line with requirements of the A-level chemistry syllabus on ionisation energy (Appendix A). By knowing their students' alternative conceptions of ionisation energy, teachers can gain a greater insight into the subject matter of the topic, their teaching, and the learning processes of their students. They are also likely to be more receptive and willing to try or develop alternative teaching strategies if they find that their present methods are inadequate in addressing students' difficulties.

Method and procedures

The two-tier multiple-choice diagnostic instrument on ionisation energy was developed in three phases using procedures defined by Treagust (1995). The first phase involved the first-named author defining the content framework of A-level ionisation energy with a concept map (Figure 1) and a list of propositional knowledge statements based on Taber's (1997a, 1999) work, an extract of the sections of the A-level chemistry syllabus relevant to ionisation energy (Appendix A), and two chemistry textbooks. The concept map and propositional knowledge were reviewed by 13 experienced A-level chemistry teachers and two tertiary chemistry educators. The reviewers agreed that the concept map and propositional knowledge statements met the requirements of the A-level chemistry syllabus on ionisation energy (Appendix A) in terms of accuracy and relevance. The assessment of the mastery of the content would then be administered in accordance to this framework and this would ensure the content validity of the assessment.

Phase Two was carried out in three stages. In Stage 1, a justification multiple-choice instrument in which students had to supply reasons for their choice of options was developed, based on the propositional knowledge statements on ionisation energy and the findings of Taber's (1999) research. The items in the instrument tested students' understanding of the factors influencing ionisation energy as well as the trend of ionisation energies across a period. This instrument was administered to eighteen Grade 11 students after they were taught ionisation energy. Another six Grade 11 students were interviewed in pairs using the instrument as the interview protocol. The results obtained led to the development of the second version of the justification multiple-choice instrument, which was administered to 146 Grade 11 and 12 students from four schools in Stage 2. The third version of the justification multiple-choice instrument, whose development was based on the results obtained in Stage 2, was administered to 130 Grade 12 students from three schools in Stage 3. 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. The data collected from Phase Two of the study was reported elsewhere (see Tan et al., 2003).

The results from the administration of the justification multiple-choice instruments and the interviews with students in Phase Two contributed to the development of the first version of the two-tier multiple-choice instrument in Phase Three. Further trials and refinement involving 283 Grade 11 and 12 students led to the development of the second version, and subsequently, the final version of the diagnostic instrument, the Ionisation Energy Diagnostic Instrument (IEDI), presented in Appendix B.

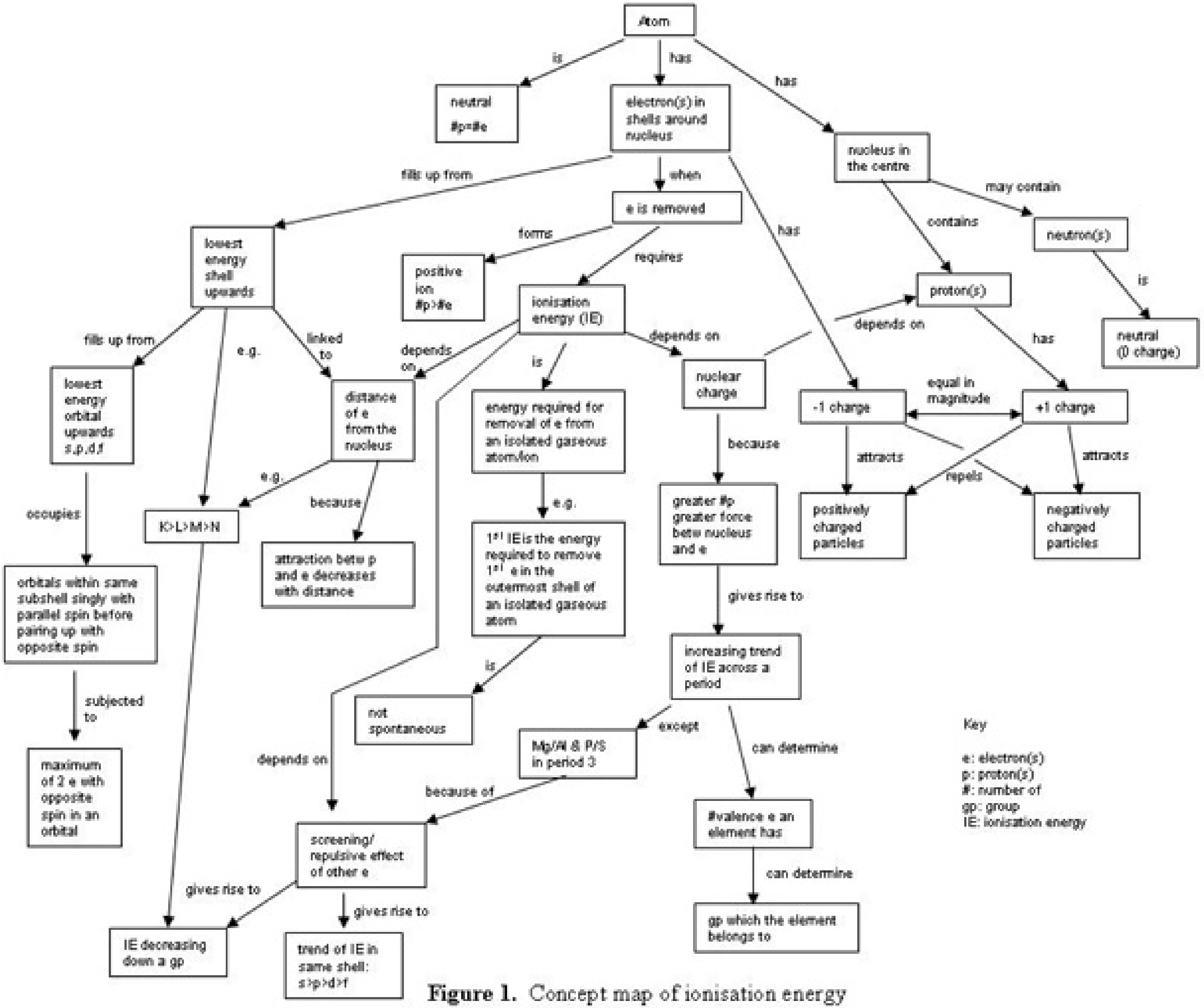


Figure 1. Concept map of ionisation energy

The IEDI was validated by five experienced A-level chemistry teachers and two tertiary chemistry educators for accuracy and relevance. The IEDI was administered to 777 Grade 11 and 202 Grade 12 students from eight out of a total of seventeen A-level institutions in Singapore in June and July 2003. Thirty-two Grade 11 and 12 students, selected by their teachers, were interviewed, either in pairs or in groups of four, using the IEDI as the protocol to determine if there was any ambiguity in the items and to further probe the thinking behind their answers. Each interview lasted between 40 minutes to an hour, and was transcribed verbatim.

Results

Table 1 describes the percentage of the Grade 11 and 12 students selecting each response combination for each item in the IEDI. The results for an item will not add up to 100% if there were students who did not select a response to both parts of the item, selected an answer combination which was beyond the options given in the item, or selected more than one answer combination.

Table 1. The percentage of Grade 11 and 12 students (n=979) selecting each response combination for each item in the IEDI

Item	Content option	Reason option					Total
		(1)	(2)	(3)	(4)	(5)	
1	A	4.8	*43.6*	3.3	-	-	51.7
	B	1.0	5.3	**38.2***	-	-	44.5
	C	0	.2	.2	-	-	0.4
2	A	6.5	.7	*49.7*	-	-	56.9
	B	**30.0***	1.4	3.7	-	-	35.1
	C	.4	.2	.4	-	-	1.0
3	A	**16.8***	.9	4.5	3.8	-	26.0
	B	1.7	1.3	2.2	*63.6*	-	68.8
	C	.1	0	.1	.4	-	0.6
4	A	*15.6*	*18.0*	**48.1***	3.6	-	85.3
	B	.1	.3	.7	1.6	-	2.7
	C	5.3	.3	.1	0	-	5.7
	D	.1	.1	0	0	-	0.2
5	A	1.2	2.2	2.9	*22.0*	4.2	32.5
	B	*13.1*	9.1	**29.2***	9.3	2.2	62.9
	C	.1	.1	.2	0	0	0.4
6	A	6.2	*48.1*	2.9	**5.4***	5.5	68.1
	B	.9	7.2	8.5	1.8	8.3	26.7
	C	.1	.1	.1	.1	.1	0.5
7	A	.5	1.8	*20.7*	*24.4*	1.5	48.9
	B	.7	5.6	7.4	6.8	**23.9***	44.4
	C	.1	0	.2	.1	.2	0.6
8	A	3.9	4.5	7.6	5.8	-	21.8
	B	5.5	*24.9*	4.6	**34.0***	-	69.0
	C	.3	.1	.1	.2	-	0.7
9	A	2.7	3.9	*19.6*	7.4	**32.1***	65.7
	B	6.8	1.6	3.5	*10.4*	4.3	26.6
	C	.2	.1	.3	.4	0	1.0
10	A	6.8	6.8	6.3	*19.0*	-	38.9
	B	3.6	3.5	**33.1***	9.0	-	49.2
	C	.3	.1	.6	.3	-	1.3

Note: Figure in bold and with an asterisk indicates the correct answer.
Figure in italics indicate a major alternative conception (>10%)

Alternative conceptions

Alternative conceptions are considered significant and common if they were found in at least 10% of the student sample (Peterson, 1986). If a higher minimum value, say 25%, was chosen, this would mean not discussing alternative conceptions that seemed likely to be found among students in many classes. Table 2 summarises the significant common alternative conceptions determined from the administration of the IEDI to the 979 A-level students. Eleven significant common alternative conceptions were identified and grouped under the headings of ‘Octet rule framework’, ‘Stable fully-filled or half-filled sub-shells’, ‘Conservation of force thinking’ and ‘Relation-based reasoning’.

Table 2. Alternative conceptions determined from the administration of the IEDI

Alternative conception	Choice combination	Percentage of students with the alternative conception
Octet rule framework		
The sodium ion will not recombine with an electron to reform the sodium atom, as its stable octet configuration would be disrupted.	Q1 (A2)	44
The Na(g) atom is a less stable system than the $Na^+(g)$ and a free electron because the $Na^+(g)$ has a stable octet configuration.	Q3 (B4)	64
The second ionisation energy of sodium is higher than its first because the stable octet would be disrupted.	Q4 (A1)	16
Stable fully-filled or half-filled sub-shells		
The first ionisation energy of sodium is less than that of magnesium because magnesium has a fully filled 3s sub-shell.	Q5 (B1)	13
The first ionisation energy of silicon is less than that of phosphorus because the 3p sub-shell of phosphorus is half-filled.	Q8 (B2)	25
The first ionisation energy of phosphorus is greater than that of sulfur because the 3p sub-shell of phosphorus is half-filled, hence it is stable.	Q9 (A3)	20
Conservation of force thinking		
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.	Q2 (A3)	50
The second ionisation energy of sodium is greater than its first ionisation energy because the same number of protons in the Na^+ ion attracts one less electron, so the attraction for the remaining electrons is stronger.	Q4 (A2)	18
Relation-based reasoning		
The first ionisation energy of magnesium is greater than that of aluminium because the 3p electron of aluminium is further from the nucleus compared to the 3s electrons of magnesium.	Q6 (A2)	48
The first ionisation energy of sodium is greater than that of aluminium because the 3p electron of aluminium experiences greater shielding from the nucleus compared to the 3s electron of sodium.	Q7 (A3)	21
The first ionisation energy of sodium is greater than that of aluminium because the 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium.	Q7 (A4)	24

Options A4 of item 5, B4 of item 9, and A4 of item 10 (see Table 3) were not considered as alternative conceptions even though they were incorrect. These questions dealt with the trend of ionisation energies across Period 3. In the items, students had to consider which important factors were in play, as well as to decide which factor outweighed the other (nuclear attraction versus electron shielding/repulsion) in the specific instance. If a student chose one of the stated options, it could indicate that he/she knew which two factors were in play, but decided wrongly on the more important factor in that specific situation. Thus, it was difficult to determine if the student had an alternative conception, or if he/she forgot or could not decide which factor outweighed the other in that specific situation. In other words, these errors are better considered failures of recall than lack of understanding of the concepts involved.

Table 3. Significant errors of students (10% or greater), which were not considered as alternative conceptions

Item	Option	Errors	Percentage of Grade 11 and 12 students
5	A4	The first ionisation energy of sodium is greater than that of magnesium because the paired electrons in the 3s orbital of magnesium experience repulsion from each other and this effect is greater than the increase in the nuclear charge in magnesium.	22
9	B4	The first ionisation energy of phosphorus is less than that of sulfur because the effect of an increase in nuclear charge in sulfur is greater than the repulsion between its 3p electrons.	10
10	A4	The first ionisation energy of silicon is greater than that of sulfur because the effect of an increase in nuclear charge in sulfur is less than the repulsion between its 3p electrons.	19

Octet rule framework

Many students (44%) thought that the sodium ion would not recombine with an electron to reform the sodium atom because the sodium ion had already achieved a noble gas configuration, and gaining an electron would cause the ion to lose its stability (Item 1, A2). In item 3, 64% agreed that the ‘sodium ion and a free electron’ system was more stable than the sodium atom because the outermost shell of the ion had achieved a stable octet/noble gas configuration (B4). When asked during interviews why an octet configuration gave the sodium ion ‘stability’, several students either stated that they were taught so, or that it was because the outermost shell of the sodium ion was filled so it could not gain or lose any electrons.

I: Why will the ion be more stable?
P14: Because octet…stable octet configuration.
I: Why is an octet configuration stable?
P14: Because it has eight electrons in the outermost shell already…so no electrons will go in, no electrons will go out…then it is very stable…to achieve a stable configuration…stable octet structure you need to have all your…shells filled… outermost shell filled.

(I represents the Interviewer, P14 represents Pupil 14.)

Cross-tabulation was used to study the consistency of the students' answers (Tan et al., 2002). Cross-tabulation of items 1 and 3 showed that only ninety students (9%) had both items correct, and 323 students (34%) consistently used the octet rule framework in both items (item 1: A2, 44%; item 3: B4, 64%). In addition, 211 students who had item 1 correct used the octet rule framework in item 3. This indicated that students could have and use both the correct concepts and the octet rule framework, even if this resulted in conflicting answers in different items. The explicit comparison of the stability of the sodium atom with the system consisting of the sodium ion and free electron could have influenced the students' use of the octet rule framework in item 3.

Students also used the octet rule framework to justify why the second ionisation energy of sodium was greater than its first ionisation energy (Item 4, A1, 16%). This differs from the curriculum model, which states that the removal of the second electron from sodium involves removing an electron from an inner (second) shell which is more strongly attracted to the nucleus as it is closer to the nucleus and experiences shielding/screening from only two electrons in the first shell. Alternatively, this last factor may be described in terms of the core charge (Taber, 2002; 2003a).

Cross-tabulation of items 1, 3 and 4 showed that only sixty-two students (6%) consistently adopted the octet rule framework in all three items (item 1: A2, 44%; item 3: B4, 64%; item 4: A1, 16%). One hundred sixty-one students (16%) who had item 4 correct used the octet rule framework in items 1 (A2, 44%) and 3 (B4, 64%), and fifty-two students (5%) who adopted the octet framework in items 1 and 3 used the conservation of force thinking (to be discussed in a later section) in item 4 (A2, 18%). The lack of consistency of alternative conceptions held by the students could point to students having more than one conception for a particular concept and "*different conceptions can be brought into play in response to different problem contexts*" (Palmer, 1999, p. 639). Taber (1999, 2000) and Voska et al. (2000) also found that students gave inconsistent answers to apparently related items. One interpretation is that students may be in the process of transition, for example, between holding an alternative conception and adopting the approved curriculum model (Taber, 2000). Caravita et al. (1994) talk about the 'meta-level' of cognitive structure where metacognitive and epistemological beliefs may influence the conceptions that are accessed and applied. Finally, the lack of consistency could also be due to students not having adequate understanding of the topic and resorting to guessing.

Stable fully-filled or half-filled sub-shells

In item 5, 13% stated that magnesium had a higher first ionisation energy than sodium because magnesium had a fully-filled 3s orbital/sub-shell which gave it stability (B1), while in items 8 and 9, 25% (B2) and 20% (A3), respectively, indicated that phosphorus had a higher first ionisation energy compared to silicon and sulfur because the 3p sub-shell of phosphorus was half-filled, hence it was stable. The excerpt of an interview below illustrates this 'stable fully-filled or half-filled sub-shell' thinking:

P14: I put B1 (item 5)…because the magnesium…the last orbital…the 3s orbital is fully filled so it will tend to be more stable…and when an orbital is either half or fully filled it will be more stable…so since sodium has only one electron in the…so when fully filled will be more stable…sodium has only one electron in the s orbital…so to be more stable it will tend…it will be easier to remove…that electron and so the ionisation energy will be lower than that of magnesium.
I: So you are saying that the first ionisation energy of magnesium is higher?
P14: It is more stable.
I: Because of the…
P14: It's fully filled orbital.

I: So why is this fully filled orbital stable…the $3s^2$?
P14: Just like in the shell…I mean…to achieve the octet structure…must have eight electrons…so when you have eight electrons in the outer shell…will be more stable… so when the orbital is fully filled then… more stable… because there's…like…more stable.
I: So stability comes with filled orbitals?
P14: Fully filled and half filled…but fully filled will have higher stability.

P14 believed that a fully-filled or half-filled sub-shell was stable because both were analogous to a 'stable octet' – there was no conflict between the octet rule framework and the 'stable fully-filled or half-filled sub-shell' thinking, in fact, the former seemed to lead 'naturally' to the latter, from shell to sub-shell. In the curriculum model, magnesium has a higher first ionisation energy than sodium because its greater nuclear charge outweighs the repulsion between its 3s electrons. A similar reason accounts for the higher first ionisation energy of phosphorus compared to silicon. However, sulfur has lower first ionisation energy than phosphorus even though sulfur has a greater nuclear charge. This is because the repulsion between the paired 3p electrons in sulfur outweighs its greater nuclear charge. The greater shielding of the 3p electron by the inner shell electrons as well as the 3s electrons explains why aluminium has a lower first ionisation energy compared to magnesium. It has to be noted that students will have great difficulty answering questions on ionisation energy trends if they cannot *either* remember whether increased nuclear charge or increased repulsion/shielding between electrons is more important in specific cases *or* recall the shape of the trend graph, and so work out which factors must be more important in each case. Thus, as mentioned earlier, it is not a matter of grave concern if students cannot decide between, for example, A4 or B3 in item 5, or A5 or B4 in item 9. However, it is problematic when students think that a fully-filled 3s sub-shell gives magnesium its stability, and hence higher first ionisation energy compared to aluminum, while phosphorus, with its 3p sub-shell half-filled, is more stable than sulfur and hence has higher first ionisation energy than sulfur.

Conservation of force thinking

Students indicated in item 2 (A3, 50%) that the nuclear attraction would be redistributed among the remaining 10 electrons when an atom of sodium loses an electron because the number of protons was the same but there was one less electron to attract. The curriculum model states that the net attraction for an electron by the nucleus depends on the number of protons in the nucleus, the distance of the electron from the nucleus and the shielding effect of other electrons in the atom. Removal of one electron from the sodium atom may reduce some repulsion between electrons causing the remaining 10 electrons to move closer to the nucleus, but the nuclear attraction for the electron which was removed is not redistributed to the remaining 10 electrons. Though conceptually incorrect, the conservation of force thinking "*does often allow correct predictions to be made (successive ionisation energies do increase) and seems to have an intuitive attraction to many students*" (Taber, 2003a, p. 156). This was shown in item 4 (A2) where 18% thought that the second ionisation energy of sodium was greater than its first because the same number of protons in sodium was attracting 10 electrons now instead of 11. The excerpt of an interview below illustrates the conservation of force thinking:

P4: Ok…I think it is true (item 2) because…like one electron is lost…the atom has one electron less, right…so…the attraction will just remain the same…so the other electrons have …greater attraction.
I: So you believe the electron…
P4: The attraction stays the same…when the electron goes out, the attraction doesn't go with the electron…so the other electrons experience greater attraction.

I: So it experiences the attraction left behind by the electron…OK P3 what is your reason?
P3: It's the same…since one electron is removed right…so the proton number is the same…so the protons has lesser electrons to attract…so the attraction force is greater …it will pull [the electrons] closer.

Cross-tabulation showed that 134 students (14%) consistently exhibited the conservation of force thinking in items 2 (A3, 50%) and 4 (A2, 18%). This indicated that students who chose the conservation of force option in item 4 were also likely to choose the similar option in item 2. Students can hold both the correct concept and alternative conception as shown by 215 students (22%) who had item 4 correct (A3, 48%) but chose the conservation of force option in item 2 (A3, 50%), and the written answer of one student, "*The same number of protons in Na^+ attracts one less electron, so the attraction for the remaining electron is stronger, moreover the second electron is located nearer to the nucleus*". There will be no cognitive conflict deriving from holding alternative conceptions like these where the conservation of force thinking and the curriculum model (as discussed above) lead to the same outcomes – in this case a greater value for the ionisation energy. Students could also hold more than one alternative framework – fifty-two students (5%) who adopted the octet rule framework options in items 1 (A2, 44%) and 3 (B4, 64%) used the conservation of force thinking in item 4 (A2, 18%), while sixty-seven students (7%) who chose the conservation of force option in item 2 (A3, 50%) selected the octet rule framework option in item 4 (A1, 16%).

Relation-based reasoning

Factors influencing ionisation energy include the nuclear charge, the distance of the electron from the nucleus and the repulsion/screening effect of the other electrons present. The results from items 5 to 10 on the trend of the first ionisation energy across Period 3 showed that many 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'*"(p. 115), and thus, overlook other possible influential factors. For example, many students indicated that the first ionisation energies of magnesium and sodium were greater than that of aluminum because the 3p electron of aluminum was further away from the nucleus than the 3s electron(s) of magnesium (item 6: A2, 48%) and sodium (item 7, A4, 24%), respectively. However, in the curriculum model, atomic radii decrease from sodium to sulfur in Period 3 because of increasing nuclear charge, which outweighs the increase in repulsion between the increasing number of electrons in the same shell.

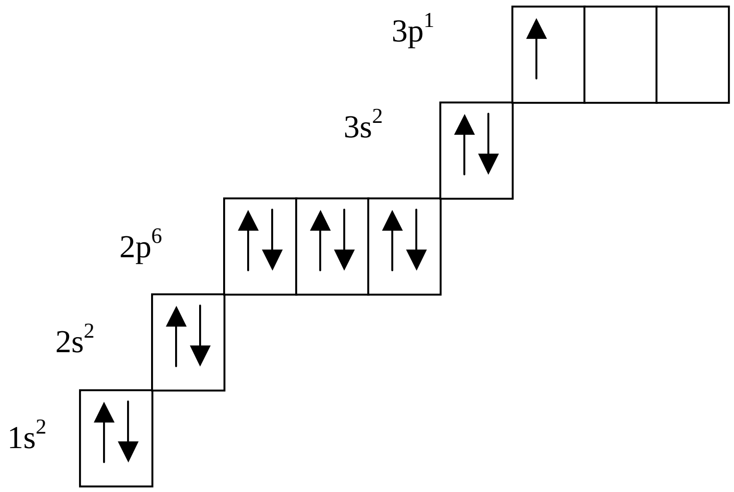
P15: I put A2 (item 6)…because the 3p electron of aluminium is further, right…so they will be further from the nucleus…because they experience…the attraction won't be so strong.
I: What made you say that the 3p electron of aluminium is further from the nucleus compared to the 3s of magnesium?
P13: We were taught that way.
P15: It's further…is taught it's further…it's taught during lectures.
P14: 1s, 2s, 2p, 3s, further, further, further.
P15: Further away.
P14: The 3p is further away.

Note that here students are remembering a comparison presented in the context of a single atomic system (e.g. 3s of sodium compared with 3p of sodium), and expecting the same pattern when the comparison is made between different systems (e.g. 3s of magnesium compared with 3p of aluminium).

P22: Because…the 3p orbital is further away from the nucleus…so…the distance…the greater the distance, the attraction is…smaller…energy used to take away the electron…the outermost electron will be smaller.
I: How do you know that the 3p electron is further away?
P22: Using the Aufbau principle.
I: And how does that help you to decide it is further away?
P22: The triangle…you know, where the 1s, 2s, 2p, 3s, 3p, and then arrow…I don't know why…the way you write $1s^2$, $2s^2$, then $2p^3$, $3s^2$, $3p^1$.
I: So you equate that as distance away.
P22: Yes.
I: OK what about you P23?
P23: Same reason as P22…but how I say the distance is different…I assume the distance by seeing the energy diagram.
I: OK…the energy diagram tells you the distance away from the…
P23: Some sort…something like that.

It would seem from the above excerpts of the interviews that students might have the idea that the 3p electron of aluminium was further away than the 3s electron of magnesium from the way they were taught to 'fill' electrons in various orbitals of an atom according to the Aufbau principle, using energy level or 'electrons-in-box' (Hill et al., 1980) diagrams (see Figure 2), or notations such as '$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$'. The diagrams or notations indicate energy levels, not distance away from the nucleus, so teachers need to be more explicit in their explanations of what the diagrams mean when they use such diagrams. Item 5 had a similar option, which stated that sodium had a higher first ionisation energy than magnesium because the 3s electrons of magnesium were further away from the nucleus (A5). However, it attracted only forty-one students (4%). This could indicate that students took the 3p sub-shell to be further away from the nucleus than the 3s sub-shell; the formalism for showing the pairing up electrons in the same 3s sub-shell of magnesium did not lead to the same

Figure 2. An 'electrons-in-box' or energy level representation of the electronic structure of aluminium



impression of moving away from the nucleus as the representation of entering an arrow into a box in a 'new' sub-shell, the 3p sub-shell of aluminium. Perhaps the same type of inference is drawn by some students when writing the additional '3p' in '…$3s^2$ $3p^1$' for the electronic configuration of aluminium as compared to magnesium, rather than just changing $3s^1$ to $3s^2$ in magnesium compared to sodium.

Another example of students using relation-based reasoning was when they indicated that sodium had a higher first ionisation energy than aluminum because the 3p electron of aluminum experienced greater shielding than the 3s electron of sodium (Item 7, A3, 24%). These students might not have considered the effect of an increase in the nuclear charge of aluminum compared to sodium.

Discussion

Since the students would hardly have encountered the concepts of ionisation energy in everyday life, it was likely that the alternative conceptions arose from the way ionisation energy was taught and learnt (Taber, 2004). The authors believe that the octet rule framework was carried over from the learning of bonding in secondary chemistry (Taber, 1997b, 1999; Tan et al., 1999) – for example, during teaching practice observations, it is common to hear pre-service teachers saying that 'the sodium atom needs to lose an electron to achieve a stable octet electronic configuration', when teaching ionic bonding. As the octet rule framework does not conflict with the accepted scientific concept in explaining why, for example, the second ionisation energy of sodium was higher than its first ionisation energy, students could unsuspectingly hold both the correct concept and alternative conception. They would see nothing wrong with the alternative conception and treat it as an additional explanation for the phenomenon.

Teachers often use 'stable fully-filled or half-filled sub-shell' as a rule-of-thumb to explain the anomaly in the ionisation energy trend across Periods 2 and 3 of the Period Table, and to help students remember the anomaly. A textbook on introductory tertiary chemistry (Lee, 1977) also uses the octet rule framework and stable fully-filled or half-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, *present authors' emphasis*)

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). As there is no conflict between the curriculum model and the 'stable fully-filled or half-filled sub-shell' reasoning in explaining why the first ionisation energy of magnesium is higher than that of sodium and aluminium, or why the first ionisation energy of phosphorus is higher than that of silicon and sulfur, the 'stable fully-filled or half-filled sub-shell' reasoning is easily accepted by students as an explanation in addition to the curriculum model; it is also easier to remember and quote. Thus, teachers need to be wary of using such heuristics in their teaching.

The conservation of force thinking could have arisen because the students did not integrate their knowledge of electrostatics learned in physics with the concepts of ionisation energy learnt in chemistry (Taber, 1998a, 2003a) or the students might not have studied A-level physics at all. As Taber (2003a) mentioned, conservation of force thinking (like the idea that full shells are desirable) has "*an intuitive attraction to many students*" (p. 156) – one will get a greater portion of a cake if there are fewer people sharing it. It also enables one to predict correctly successive ionisation energies. If only one or two of the three factors influencing ionisation energy (nuclear charge, distance from the nucleus and shielding/ screening effect) were used during lessons to discuss the difference in ionisation energies of two or more elements, then students are not likely to realise that they had to consider all three factors, not just one or two; this could be the cause of relation-based thinking.

It is worth noting that the lack of consistency found in the principles used to answer the earlier questions in the IEDI (Q1-4), and the use of relation-based thinking in the later items (Q5-10), may be closely related phenomena. So those students who, for example, used appropriate electrostatic ideas to answer Q1 but were attracted to the idea that full shells imply stability in Q3, may be selecting what seems the most appropriate response from a repertoire of potentially relevant principles (in itself, a sound strategy, cf. Taber, 1995), in the same way as those who used ideas about, say, increased shielding whilst ignoring increased nuclear charge when comparing elements in Period 3. In one situation the students are selecting from alternatives with different status relative to the curriculum ('alternative' conceptions vs. appropriate concepts), and in the other situation they are selecting only one of the relevant appropriate alternatives – so in both cases they judge one of a number of potentially relevant explanatory principles as 'the' best answer in the context of a particular item.

Teachers need to be aware that they can be the sources of alternative conceptions, for instance, by the way they teach – using the 'stable fully-filled or half-filled sub-shell' heuristics. Teachers can also have the same alternative conceptions as students (Wandersee et al., 1994; Chang, 1999; Lin et al., 2000; Tan, 2005) and can unwittingly pass their own alternative conceptions to their students, or think that there is nothing wrong with their students' alternative conceptions. Pre-service teachers' understanding of ionisation energy is being investigated as an extension of this study; the IEDI has so far been administered to 105 pre-service secondary chemistry teachers, and four pre-service teachers were interviewed using the IEDI as the protocol. When the four pre-service teachers were asked in interviews to explain the trend of ionisation energy across the elements, sodium to aluminium, and silicon to sulfur, and all of them referred to the 'stable fully-filled s sub-shell' and 'stable half-filled p sub-shell' heuristics in addition to the correct concepts in their explanations. Teachers should also realise that textbooks also can contain errors and misleading or conflicting illustrations and statements that can give rise to alternative conceptions (Wandersee et al., 1994; Boo, 1998; de Posada, 1999; Sanger & Greenbowe, 1999).

The results and conclusions generated in this study refer specifically to the sample groups involved in the study. Generalisation of the findings to all A-level chemistry students in Singapore must be considered with caution due to the nature and the limited number of A-level institutions involved in the study. Not all concepts and propositions related to A-level ionisation energy were measured by the IEDI, so the conclusions refer specifically to the concepts and propositions examined by the test items. There are also problems associated with the pencil-and-paper tests (Towns et al., 1993). For example, multiple-choice tests "*make some demands on the reading/comprehension skills of the respondents*" (Taber, 1999, p. 99), and students do not "*always perceive and interpret test statements in the way that test designers intend*" (Hodson, 1993, p. 97). Students may not understand or may misinterpret the questions and options in the IEDI, and since they have little recourse for clarification, this may affect the validity and reliability of the test. However, the interviews included in the present study provide triangulation for the IEDI, and suggest this was not a major problem in the present research.

Conclusions: implications for teaching and research

The findings from this application of a two-tier diagnostic instrument developed and administered to Grade 11 and 12 chemistry students lead us to make a number of recommendations and suggestions relating to the teaching of this topic, and to the direction of further research. It seems clear from this study that many A-level chemistry students in Singapore (as in the UK) have significant difficulties in building up an understanding of ionisation energies that matches the target knowledge in the curriculum. This implies that the current approach to teaching this topic is ineffective. Our research leads to some suggestions for how teachers may adjust their teaching of this topic, but also raises questions about its place in the curriculum that indicate the need for further research.

One key area highlighted in this study was how students apply invalid explanatory principles based on the inherent stability of octets or full shells, and on notions of sharing-out of nuclear attraction. We have explained how the octet rule framework is likely to have been developed during earlier secondary education, and is often encouraged by the language and forms of explanations used by some teachers and textbooks. Teachers need to be careful that when discussing ionisation energy they do not use metaphorical language such as atoms ‘wanting’ complete shells that may imply that these shells have an inherent stability. However, as many students will already be primed to think in this way from previous studies, it is also important for teachers to be very alert and spot when students demonstrate this type of thinking, so they may challenge any statements of this form to create dissatisfaction in the students with their alternative conception in order for conceptual change to take place (Posner et al., 1982). As students readily assign similar stability to full sub-shells or half-filled sub-shells, the same advice applies in these contexts. Anthropomorphic language has its place in science and in learning science (Taber et al., 1996), so teachers should be careful not to ridicule student comments about what atoms ‘want’ or ‘need’. However, teachers should always use such student comments as an opportunity to develop a more scientific understanding: responding by asking the student if they can rephrase their point in more technical language. If not, the teacher should model an explanation using scientifically valid ideas, in the appropriate language.

Teachers should emphasize electrical interactions at all times, and make connections with basic electrostatic (i.e. Coulombic) principles to challenge the common notion that the nucleus gives out a set amount of force, that is somehow shared around the electrons. Teachers should also be careful that whenever using formalisms such as the electrons-in-boxes representations, they should be explicit about the significance of the representation, and check that students appreciate which is signified.

The second area of concern from this study is the way students coordinate (or fail to coordinate) different potential factors that may be significant in making comparisons. What seems clear from the pattern of responses in this study, is that many students seem to be aware of a range of potentially relevant factors (some scientifically valid, some not) that can influence ionisation energy. However, they may be using a faulty ‘search’ strategy (i.e. ‘identify a single relevant factor, and apply it’), or are actually identifying all the relevant factors, but are not able to coordinate them effectively. In the latter case, we need to appreciate whether this is simply a lack of having been taught a suitable strategy - in finding a way to overcome limitations in working memory, (cf. Tsaparlis, 1994, 1998), or whether it indicates a mismatch between cognitive abilities and demands (cf. Shayer et al., 1981). We suspect that when many students are asked to make a comparison between two ionisation processes, they bring to mind one apparently relevant factor and apply it on an 'all other things being equal'. Thus, they may notice that a magnesium atom has one more electron than a sodium atom but not consider that it also has one more proton in its nucleus.

More research is needed to explore this issue, but for the moment our advice to teachers is that when discussing ionisation energies, and making comparisons, they should always be explicit about all the factors that should be considered (even when some are not relevant for a particular comparison). So, for example, in comparing the second and third ionisations of sodium the teacher should ensure that nuclear or core charge is considered, even though in this case it will be seen that this has not changed and so can then be put aside as a consideration. In this way, the teacher can model the process of always identifying the potential factors at work, and so making decisions about which need to be taken into account in any particular case. Sometimes some factors can be ignored, sometimes influencing factors have effects in the same direction, and sometimes there is a degree of compensation – in this case a student can decide on the dominant factor(s) only by looking at the experimental data.

Ionisation energy is a topic that has historically featured in courses at this level, but this inclusion should be questioned if educational research suggests that most learners are unlikely to cope with the concepts at this stage of their scientific education. It may be that many 16-19 years olds do not yet have the cognitive ability to coordinate a range of factors, in the context of formal models of atomic structure, or (as implied above) perhaps they lack support in developing strategies that would enable them to respond. Either difficulty assumes that students have the required knowledge, *and* can access it for processing. Research into A-level students' understanding of 'orbital' models of the atoms (Taber, 2004) suggests another possibility. Here it was found that even when students could clearly demonstrate they had acquired an 'orbital' model of the atom that matched that presented as curriculum knowledge, they had difficulty applying that model in appropriate contexts. It was suggested that although the new knowledge was established well enough to be recalled when cued, it was not yet robust enough to act as the basis of further learning. This conjecture derives from research into memory formation, which indicates that consolidation of new learning typically occurs over a time-scale of many months (see Taber, 2003b). The content of school science is determined by a range of considerations, and is not always 'educationally sound' (Kind & Taber, 2005). Educational research should provide the educational community with the basis for making choices about curriculum content, and in designing the curriculum models that are appropriate for different learners.

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