EXPLORING LEARNERS' CONCEPTUAL RESOURCES: SINGAPORE A LEVEL STUDENTS' EXPLANATIONS IN THE TOPIC OF IONISATION ENERGY

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Abstract

This paper describes findings from a study to explore Singapore A-level (Grade 11 and 12, 16 to 19 years old) students' understanding of ionisation energy, an abstract and complex topic that features in school chemistry courses. Previous research had reported that students in the United Kingdom commonly used alternative notions based on the perceived stability of full shells and the 'sharing out' of nuclear force, but that such ideas tended to be applied inconsistently. This paper describes results from the administration of a two-tier multiple-choice instrument, the Ionisation Energy Diagnostic Instrument, to find (1) whether A-level students in Singapore have similar ways of thinking about the factors influencing ionisation energy as reported from their A-level counterparts in the UK; (2) how Singapore A-level students explain the trend of ionisation energy across different elements in Period 3. The results indicate that students in Singapore use the same alternative ideas as those in the UK, and also a related alternative notion. The study also demonstrated considerable inconsistency in the way students responded to related items. The potential significance of the findings to student understanding of complex topics across the sciences is considered.

Key words: conceptual resources; diagnostic assessment; ionisation energy; two-tier multiple-choice test; knowledge-in-pieces; p-prims.

INTRODUCTION

Students are often found to have difficulty learning science in the school curriculum, especially where the target knowledge is highly abstract and complex. A substantial body of research in science education over recent decades has explored student understanding of science topics, looking to inform curriculum design and teaching strategies (Duit, 1991, 2006; Driver, Squires, Rushworth & Wood-Robinson, 1994; Taber, 2002). Findings have been conceptualised in a number of ways: for example as intuitive theories, preconceptions, alternative conceptual frameworks, or as knowledge-in-pieces.

Some studies have reported stable theory-like thinking leading to consistent patterns of alternative responses in answering questions about topics. Other researchers have characterized ideas elicited from learners as more tentative, context-bound and labile. That research offers evidence for such a range of views on the nature of student's knowledge of science topics suggests that this is a multi-facetted phenomenon, where the nature of student thinking will be influenced by various aspects of the topic, the prior experience and intellectual development of the learner, the nature of the teaching etc. (Taber, 2006). It seems a good deal more research is needed to clarify the various interactions influencing the ideas that students produce during science courses.

The present paper presents findings from a study exploring aspects of thinking about an abstract and complex topic prescribed in senior school chemistry courses – ionisation energy. This topic offers some interesting insights because it has previously been reported that students' thinking appears to demonstrate both common recurring patterns of alternative thinking and inconsistencies in the way individual learners respond to different specific questions that are similar from a scientific perspective.

The abstract and complex nature of science in the curriculum

Science topics in secondary and college level courses often present material that is highly abstract for students, and it is well recognized that this can pose a challenge in terms of the level of intellectual development of many learners (e.g. Shayer and Adey, 1981). Concepts such as energy, or redox, or gene, are highly abstract, and research into student understanding of such concept areas shows that learners often develop their own ‘alternative’ meanings and understandings that do not match the accepted scientific models (or more correctly, the simplifications of those models presented in the curriculum as target knowledge). As learners proceed to higher grade levels, they are asked to consider topics which are increasingly *complex* as well as abstract. Many learners apply ‘linear causal thinking’ (Driver, Leach, Millar & Scott, 1996) to such systems (such as electric circuits), considering causal links sequentially, and in isolation from each other.

This present paper considers results from a study to investigate student understanding of a science topic of high conceptual demand. Ionisation energy is an important topic in many chemistry courses, including the A-level courses followed by students in the UK and Singapore. Previous research (discussed below) has described student difficulties in understanding this topic in the UK, and the study considered here was designed to follow-up and extend the UK research among students in Singapore.

As well as being an important topic in its own right within chemistry education, ionisation energy offers science education an example of a topic where students are required to deal with both a high level of abstraction, and a degree of complexity. Research into understanding this topic could therefore prove informative for researchers exploring student learning of other complex concept areas. There are many such areas in school and college science – homeostasis, natural selection, exponential decay, chemical equilibrium etc.

This is a topic that builds upon prior understanding of atomic structure, and which requires application of the concepts of energy and force – areas known to present difficulties to many learners (e.g. Watts, 1983a, 1983b; Harrison & Treagust, 1996; Taber 2003a, 2004). The topic is complex, because in order to explain the various trends in ionisation energy (down groups; across periods; successive ionisations of the same atom) that students are required to understand, they must consider a range of factors (nuclear charge; electron-nucleus separation; number of 'shielding electrons' in shells 'inside' the outer shell; number of electrons in the same shell; net charge on remainder of atom/ion as it is ionized; type of orbital occupied by the electron; whether there is another electron in the same orbital).

The nature of learners' thinking in science: facets of cognitive structure

Much of the research exploring learners' ideas about, and understanding of, science topics has been framed in terms of 'misconceptions', 'alternative conceptions' or 'alternative frameworks' (Driver & Erickson, 1983; Gilbert, & Watts, 1983). The general understanding is that these are features stored in memory in some form, and activated as integral units.

Other authors have interpreted research data from studies into students' ideas as implying that learners' thinking tends to be incoherent and inconsistent, fragmentary and transient (e.g. Claxton, 1993; Solomon, 1992, 1993; Viennot 1979) - and perhaps sometimes simply created in response to the social pressure of the researcher's questions (Solomon, 1993). From this perspective, the cognitive resources students draw upon when responding to questions (in class, in tests, in research interviews) are *in themselves* stable aspects of thinking, but – like the bricks used in building houses – are used as components of a novel structure constructed in response to a specific context.

Conceptual resources as 'knowledge-in-pieces'

Smith, diSessa & Roschelle (1993) suggest that there must be fundamental or primitive elements of cognition that learners use to construct their conceptions and conceptual frameworks. DiSessa (1993) proposed such a class of "hypothetical knowledge structures" called phenomenological primitives, or 'p-prims' that could act as "primitive elements of cognitive mechanism - as atomic and isolated a mental structure as one can find" (p.112).

From this perspective, the person has 'knowledge-in-pieces' – i.e. conceptual resources that can act as the elements for constructing knowledge *in situ*. It is suggested that learners construct conceptual structures from primitive elements, and if these structures are found to be useful and so consolidated through repeated use, they themselves become stable aspects of cognition. A knowledge-in-pieces account may be particularly useful in explaining research that elicits inconsistent responses from the students. Even when the students acknowledge that they are being inconsistent in their use of ideas, it is possible that they are inconsistently selecting from a range of stable, pre-existing, notions (Taber, 2000 cf. Mortimer, 1995).

Student understanding of ionization energy

Taber has reported studies exploring how A-level (General Certificate of Education 'Advanced' level) students in the UK understand and explain patterns of ionisation energy. The initial work was based on in-depth interviews (Taber, 1998), and this was followed by the development and application of a diagnostic instrument (based around the example of ionization of a sodium atom). The 30 item 'truth about ionization energy' diagnostic instrument was administered to 110 A-level students in one UK college (Taber, 1999), and this was later followed by a larger scale study involving 334 students from 17 schools and colleges (Taber, 2003b).

Table 1 about here

In Taber's UK studies, students commonly misunderstood the scientific (i.e. curriculum) model for explaining and predicting trends in ionisation energy, as summarized in Table 1. Taber (2003b) described his findings in terms of a number of 'alternative conceptions'. In particular, students commonly used the scientifically invalid ideas that (a) ions with full shells had some special inherent stability ('full shells or octet rule thinking'), and (b) a positive nucleus gives rise to a fixed amount of nuclear force that is distributed or shared-out among the electrons present ('conservation of force thinking'). In the UK studies, statements reflecting these two ideas were judged as true by most of the samples of A-level students. The items based on 'conservation of force thinking' were considered true by between 55% and 72% of respondents, and items based on 'octet-rule thinking' were judged true by between 52% and 83% of the students. The response patterns in Taber's (1999, 2003b) results also indicated some students were judging the truth of related statements in inconsistent ways.

PURPOSE

The diagnostic instrument used in the UK studies (Taber, 1999, 2003b) was designed around specific aspects of thinking that had previously been elicited in interviews (Taber 1998) and did not explore understanding of trends in ionisation energies across periods, although this is also specified knowledge in the A-level chemistry syllabus. The study discussed here used a two-tier multiple-choice diagnostic instrument to explore two research questions:

(1) Do A-level students in Singapore have similar ways of thinking about the factors influencing ionisation energy as their A-level counterparts in the UK?

(2) How do Singapore A-level students' explain the trend of ionisation energy across different elements in Period 3?

METHOD AND PROCEDURES

In this study, a two-tier multiple-choice instrument (Treagust, 1995) was developed and applied to determine students' understanding of the concepts involved in ionisation energy. Items in a two-tier multiple-choice diagnostic instrument are designed to identify misunderstandings in a limited and clearly defined content area. The first part of each item consists of a multiple-choice content question usually having 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. Incorrect reasons (distracters) are derived from examples of actual student thinking gathered from the literature, interviews and free response tests. This methodology has previously been used to develop diagnostic tests in a range of science topics (e.g. Peterson, Treagust, & Garnett, 1989; Tan & Treagust, 1999; Tyson, Treagust, & Bucat, 1999; Tan, Goh, Chia & Treagust, 2002).

The two-tier multiple-choice diagnostic instrument on ionisation energy was developed in three phases using procedures defined by Treagust (1995). This involved conceptual analysis of the topic, interviewing students, and several stages of piloting of the instrument. A detailed account of the development process is given in Tan, Goh, Chia & Taber (2005), where the final version of the Instrument is available.

The Ionisation Energy Diagnostic Instrument (IEDI) was administered to 777 Grade 11 and 202 Grade 12 students (Tan, Taber, Goh & Chia, 2005) from eight out of the total of 17 A-level institutions in Singapore, in June and July 2003 (see Table 2).

Table 2 about here

RESULTS

The response sheets were optically scanned, and SPSS version 11 was used to analyse the results. Following the procedure in Peterson (1986), an item was considered to be correctly answered if a student correctly responded to both parts of the item. A small number of students gave more than one response on some items, or offered their own alternative (which they were invited to do if they judged that none of the responses offered matched their thinking). However, these instances (31 and 42 respectively) made up a small fraction of the responses.

The proportion of students selecting the correct response varied considerably, but was less than half for each item. The mean score on the instrument was 2.9 (/10) suggesting that, like their UK counterparts, many students in Singapore have difficulties with this curriculum topic. Only one-fifth of the students gave correct responses to half or more of the ten items (Tan, Taber, Goh & Chia, 2005).

Common alternative responses

Peterson (1986) has suggested that in this type of instrument, alternative (i.e. incorrect) responses should be considered important if they are selected by at least 10% of the sample. In the present study, there were 14 such common alternative responses. Three of the common incorrect responses were considered as errors in judging the relative importance of factors tending to have opposing effects. These questions dealt with the trend of ionisation energy across Period 3. In the items, students had to consider which important factors were in play, and then decide which of the opposing factors outweighed the other (nuclear attraction versus electron shielding/repulsion) in the specific instance. As no data were provided to students, these errors may be better considered failures of recall, rather than lack of understanding of the concepts involved. The other common errors are considered to be indicative of student thinking which is at odds with the scientific models presented in the curriculum. These are shown in Table 3, grouped thematically in terms of the type of thinking involved.

Table 3 about here.

Octet rule thinking

Responses reflecting thinking in terms of the perceived stability of particular electronic structures were commonly chosen as explanations for some items. Three of the items offered detractors in terms of noble gas electronic structures (i.e. equivalent to 'octets' or 'full shells' of electrons). 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. 64% agreed that the 'sodium ion and a free electron' system is more stable than the sodium atom because the outermost shell of the ion has achieved a stable octet/noble gas configuration. Some, though fewer (16%), students also used full shells thinking to justify why the second ionisation energy of sodium was greater than its first ionisation energy. Six students indicated on their answer sheets that they had two reasons (option 1 – stable configuration and option 3 – inner shell) to support their answer that the second ionisation energy of sodium was greater than its first ionisation energy.

Stable sub-shells thinking

13% selected an option that magnesium had a higher first ionisation energy than sodium because magnesium had a fully-filled 3s orbital/sub-shell which gave it stability. 25% and 20% of the sample, 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 providing stability. 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 and to some extent by the 3s electrons (something that would not be predicted from the 'shell' model of atomic structure) explains why aluminium has a lower first ionisation energy compared to magnesium.

Conservation of force thinking

50% of the students in the sample indicated 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 attraction for an electron by the nucleus depends on the number of protons in the nucleus, and the distance of the electron from the nucleus (although the effect may be moderated by the shielding effect of other electrons in the atom). Removal of one electron from an atom may reduce the repulsion between electrons (especially those in the same shell) causing the remaining 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, 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, 2003b, p. 156). 18% of the sample 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.

Relation-based reasoning

Factors influencing ionisation energy of an atom 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 IEDI items on the trend of the first ionisation energy across Period 3 showed that many students did not consider all the relevant factors in an example, 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, 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 compared to the 3s electron(s) of magnesium (48%) and sodium (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. Here students may be applying a comparison presented in the context of a single atomic system (e.g. 3s of hydrogen compared with 3p of hydrogen), and expecting the same pattern when the comparison is made between different systems (e.g. 3s of magnesium compared with 3p of aluminium), i.e., they are ignoring key relevant features of the comparison.

Another example of students using relation-based reasoning was when 21% of the sample indicated that sodium had a higher first ionisation energy than aluminum because the 3p electron of aluminum experienced greater shielding compared to the 3s electron of sodium. These students appear to have ignored the effect of an increase in the nuclear charge of aluminum compared to sodium.

Consistency of student thinking

It is clear from table 3 that although some alternative (‘incorrect’) ways of thinking about ionization energy were common, these were not used consistently, so that the percentages of students selecting an alternative explanation varied considerably between items. For example, approximately three-fifths of respondents thought that the octet of electrons made the sodium ion more stable than the atom, yet only about two-fifths thought that this stability would prevent the ion and electron recombining, and less than one fifth of the students used this stability as the reason for the higher second ionization energy.

Some students would use both the correct concepts and alternative modes of thinking, applying a different way of thinking to different items. Cross-tabulation of items where the same curriculum ideas should be applied showed many examples where students were switching between the accepted and alternative ideas. For example, only 90 students (9%) used the appropriate curriculum ideas to explain both whether a sodium (Na^+) ion and electron would combine, *and* whether the atom was more stable than the ion and separated electron. A greater number of students (211) who answered the former item correctly, shifted to octet rule thinking for the latter item. A greater number still (323 students, 34%) consistently used octet rule thinking in both items. However, only 62 students (6%) consistently chose the option based on octet rule thinking in all three items where it could be selected. Similar patterns of inconsistent responses were found when cross-tabulating other combinations of items (Tan, Goh Chia & Taber, 2005).

DISCUSSION

Previous interview-based research in the UK had uncovered common 'alternative' ways that students think about the curriculum topic of ionisation energies: in particular in terms of the stability of octets (or full shells) of electrons, and in terms of the sharing-out of a conserved quantity of nuclear force among electrons (Taber, 1998). Surveys with a simple diagnostic instrument suggested that response options based on these ways of thinking were commonly selected by UK students (Taber, 1999, 2003b). It was reported that response patterns indicated that some students were inconsistent in their selection of responses to different items.

The present paper considers a study to replicate (research question 1) and extend (research question 2) the research among the equivalent population of students in Singapore. The Singapore research surveyed almost a thousand students with a two-tier diagnostic instrument (Tan, Goh, Chia & Taber, 2005). This study has shown that explanations based on (a) the stability of octets, and (b) the conservation of nuclear force, are commonly selected by students in Singapore. In terms of research question question 1, our findings suggest that A-level students in Singapore have similar ways of thinking about the factors influencing ionisation energy as their A-level counterparts in the UK.

The inclusion of a wider range of question contexts than in the UK study allowed us to address our second research question (i.e. how do Singapore A-level students' explain the trend of ionisation energy across different elements in Period 3). We found that explanations in terms of the stability of filled or half-filled sub-shells were elected by A-level students in Singapore. The two-tier nature of the instrument used in the present study also revealed that some students did not appreciate how a change in one factor (e.g. increase in electronic shielding in magnesium compared to sodium) might be cancelled or overcompensated by the co-variation in another (e.g. increase in nuclear charge in magnesium compared to sodium).

Inconsistencies consistent with knowledge-in-pieces

A key finding from the survey of Singapore students is that not only were the previously identified 'alternative' ways of thinking about this topic the basis of common responses, but the inconsistency found in the UK research was also a feature of student thinking in the Singapore sample (Tan, Taber, Goh & Chia, 2005). Interviews carried out with a sample of the Singapore population (Tan, Goh, Chia & Taber, 2005) found that the same ways of thinking were reflected in the answers given in a semi-structured interview situation. This suggests that such response patterns are an authentic reflection of the inconsistent way that many students think about this topic.

It would seem that students bring a range of conceptual resources to their thinking about ionisation energy. This in itself is appropriate: ionisation energy is a complex topic where students are expected to appreciate how of a range of factors are relevant in different particular examples. For example, students need to realise that in comparing the first ionisation of sodium and potassium, both of which are in Group I, the difference in nuclear charge is countered by an increase in electronic shielding, and so the difference in electron-nucleus separation will be the significant factor. However, when comparing between elements in the same period, several factors are changing at once: nuclear charge; electron-nuclear distance; in some cases, type of orbital; in some cases, the occupancy of an orbital. In these comparisons, several potentially relevant factors have to be considered, and weighed.

Complexity as a barrier to student understanding

The present study suggests then that students may have two areas of difficulty in answering questions about this topic. As well as the significance of students' ways of thinking that are inconsistent with the curriculum models, there are additional complications directly related to the *complexity* of the topic. When several potentially relevant factors in making a comparison vary, students often seem to lack the ability to identify the factors involved and decide what the overall effect may be.

It is important to understand why this is, if teachers are to know how to respond. For example, it may be that some students use a 'search strategy' that involves looking to recall a likely relevant factor, and then simply work with the first one identified. This would clearly be a different problem from where a student does identify all the relevant factors, but does not know how to relate and coordinate them. In the former case students need to be given a new strategy for dealing with questions about complex issues: for example, being given a metaphor for their available conceptual resources as a toolkit (Taber, 1995) from which they need to identify the best (not just any applicable) tool. If the problem is not one of identifying factors, but of coordinating them, then they may need strategies that help them better use limited working memory to organise problem spaces (Glynn, Yeany & Britton, 1991).

Conceptual repertoires as a barrier to understanding

The set of resources that students are selecting from include both appropriate and inappropriate elements. The knowledge-in-pieces approach, considering student responses to the diagnostic instrument to reflect how they hold a repertoire of cognitive resources from which to select a response in the context of specific questions, offers a feasible mechanism to explain why there is such inconsistency in students' responses. From this perspective, the highly abstract topic of ionising atoms is modelled using notions built up from a range of primitive patterns that have been found to be productive in other contexts. For example, the notion that (all other things being equal) an electron closer to the nucleus is harder to remove would seem to reflect a general primitive pattern that 'closer means stronger', and this intuition serves well. Similarly, the idea that (all other things being equal) a larger nuclear charge will attract an electron more would seem to be intuitive, following a 'more means stronger' primitive. There are many situations where effects diminish with distance from a source, and many situations where more of something has a greater effect. Similarly, the notion of octets or full shells (or for that matter sub-shells) being stable has an intuitive appeal. A whole or complete shell might be expected to be harder to disrupt than one that is incomplete or had already been 'broken into'. Incomplete structures are generally unstable, and there are many structures that become considerably weakened once damaged at one point. That half-filled sub-shells are also seen as inherently stable suggests that a primitive intuition about the significance of symmetry may well be at work here.

'Sharing out' is a common pattern that seems suitable for readily being abstracted into a p-prim. Young children will find that the more guests at their party, the less sweets each one gets, and there are many other examples that will form part of common experience – thus it may seem 'natural' that the 'nuclear force' must also be shared around. The common notion that the outermost electrons in a species with more electrons will be further from the nucleus can also be interpreted in terms of a common pattern that is a likely candidate for a p-prim, i.e. 'more means bigger'. This pattern is very common in everyday experience, where increasing the amount of something, or having more units, usually leads to something larger.

LIMITATIONS OF THE STUDY

The sample in the present study comprises of 979 A-level students from eight of the 17 institutions teaching this course in Singapore. Although this is a substantial sample, and the range of institutions guards against excess influences from idiosyncratic teaching, the sample was not designed to be statistically representative of the population. For this reason, the *precise* response patterns in the sample should be considered as *indicative* of student thinking in the wider population.

There are some issues of concern associated with the pencil-and-paper tests. For example, multiple-choice tests make demands on student comprehension, and may not be interpreted in the ways intended by researchers. Also, any kind of closed-response instrument may not offer options that students feel are ideally matched to their own understanding, even when authentic student ideas are used in the development of an instrument. The limited number of distracters that can be given in a question means that only the most common patterns of thinking are likely to be diagnosed

In this study, the IEDI was informed by the target knowledge in the prescribed curriculum, and the findings from UK research with a comparable sample (students studying for the same qualification). The items were developed through several phases. A range of safeguards, including checks on face validity of items, piloting, and interviewing (Tan, Goh, Chia & Taber, 2005) allow us to be confident that findings from the IEDI do reflect student thinking about this topic.

CONCLUSIONS

The two-tier diagnostic instrument showed that students in Singapore applied the same octet rule thinking and conservation of force thinking to explain the factors influencing ionisation energy as has been reported the UK. Many students in Singapore also resorted to relation-based reasoning to explain the trend of ionisation energy across Period 3 elements. The *specific* findings from this study, and earlier related research, can be useful to high school and college teachers when preparing to teach this topic.

The results also showed that students can hold a repertoire of conceptual resources ('knowledge-in-pieces') that they perceive as relevant to this topic, but which they do not apply consistently. Some of these conceptual resources are quite appropriate, but others contradict scientific thinking. We suggest that the types of patterns of thinking found here would seem to relate to the nature of this curriculum topic as highly abstract and requiring students to consider a range of potential influences as work. Similar patterns of thinking (i.e. inconsistent application of an eclectic mixture of appropriate and inappropriate ideas) may also occur in student thinking about other science topics of similar levels of abstraction and complexity. This suggests an avenue for future research. It is also important to know more about the process that allows primitive elements to be built up. There is clearly scope here for learning a lot more about how teachers can guide learners to construct appropriate ideas from the available cognitive resources.

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Table 1: Aspects of student thinking relevant to ionisation energies reported in previous studies.

student thinking	scientific thinking
The sodium atom would be more stable if its 3s electron is removed, as this gives an ion with a full shell.	Work has to be done to remove the negative electron which is attracted to the nucleus, so the atom is more stable than the separated ion and electron
If the outer electron of sodium is removed, it will not return because the sodium ion has a full outer shell and so achieves a stable electronic configuration	If the negative electron is removed it will leave a positive ion and they will be attracted back together (unless prevented)
Only one electron can be removed from sodium because of the stable configuration of the sodium ion which has a full outer shell	More energy is required to remove a second electron, because the electrical force acting on it during ionization is greater as is removed from a 'shell' closer to the nucleus (and from a more positive species)
Sodium 7^- ion (Na^{7-}) is more stable than the sodium atom because it has a full outer shell	The sodium 7^- ion would be highly unstable, and could not form except under very extreme conditions
Each proton attracts only one electron	All positive protons attract, and are attracted to, all negative electrons
Nuclear charge gives rise to a certain amount of attractive force that is shared between the electrons	The force between any particular two charges depends only on the magnitude of those charges and the separation between them
Once an electron is removed, the remaining electrons receive an extra share of the attraction from the nucleus	When an electron is removed, the other electrons may be more firmly bound in the atom due to the effects of reduced repulsion between electrons

Note: students in the UK tended to refer to full shells, more than octets or noble gas configurations. The Na^{7-} species would not have a full outer shell, but nonetheless is often described in these terms (Taber, 2002).

Table 2: Distribution of students over schools

School	Grade	Female	Male	Total
81	12	76	71	147
82	11	72	57	129
83	11	35	40	75
84	11	81	66	147
85	11	77	80	157
86	12	31	22	53
87	11	110	75	185
88	11	17	29	46
Total		499	440	939
		(53.1%)	(46.9%)	(100%)

Note: 40 students did not state their gender

Table 3: Common patterns in alternative responses determined from the administration of the IEDI

Alternative response	Choice combination	Percentage of students giving response
Octet rule thinking		
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 attract 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