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UNDERSTANDING IONISATION ENERGY: PHYSICAL, CHEMICAL AND ALTERNATIVE CONCEPTIONS

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ABSTRACT: There are many topics in chemistry where student performance in formal assessments may be considered to largely depend upon the understanding and application of concepts that may be un-problematically labelled 'chemical': concepts such as 'element', 'neutralisation', 'addition reaction', etc. However, there are also a number of curriculum topics from within chemistry where students are required to be able to demonstrate and apply ideas which in themselves may be seen as 'belonging' more to physics than chemistry. One such topic is that of ionisation energy, where basic electrostatic principles must be understood and applied. This paper discusses responses to a diagnostic instrument on Ionisation Energy which highlight student difficulties appreciating conventional physical principles. The instrument comprised 30 true-false items and was administered to over 300 college level chemistry students in 17 institutions in the UK. Respondents commonly agreed with statements reflecting previously identified alternative conceptions relating to the 'sharing' of nuclear force, and to the unconditional stability of species with full shells. The implications of the findings for the teaching of chemistry are considered, with particular reference to the debate about the extent to which chemistry can or should be reduced to physics. [*Chem. Educ. Res. Pract.*: 2003, 4, 149-169]

KEY WORDS: *chemistry & physics; chemical concepts; ionisation energy; alternative conceptions; 'conservation of force' conception; 'full shells' shells explanatory principle; explanations in chemistry; understanding atomic structure*

INTRODUCTION

Relating topics in science: physics and chemistry

Physical science is by its nature a highly inter-linked area of knowledge, and much of the material in the school curriculum suggests the need for logical sequencing of presentations. In chemistry, topics such as the periodic table, acids and bases, redox, bonding and structure etc. provide organising principles which are drawn upon in other topics (Fensham, 1975). Understanding the particle model of matter, the distinctions between elements, compounds and mixtures, and the representation of reactions (and of the conservation of matter during reactions) through chemical equations are pre-requisite knowledge for much of the subject. It would certainly be possible to design a curriculum without these key concepts, but the resulting subject would lack the ability to present chemistry as a systematic area of knowledge (which is surely a key criterion for something we would wish to call a science).

Similar principles operate in physics (Golab-Meyer, 1985): understanding of d.c. circuit principles is important before a.c. is tackled; linear dynamics is taught before, and used as a basis for teaching, rotational dynamics; and so forth.

There are also many areas of overlap between chemistry and physics. Students taking discrete college (sixth form, or high school) courses in both subjects may well find they are taught about radioactivity and thermodynamics in both courses. Where the teachers concerned liaise over their planning, this repetition can be helpful for students - but there is also the possibility of different approaches and conventions to confuse students. In a similar way, when particle theory is first met during secondary school (i.e. as the principle that everything is made of tiny particles, perhaps two or three years before any exploration of the nature and structure of these particles is introduced), it is possible for the quanta of matter to be described as atoms in physics but molecules in chemistry (Taber, 2001a).

As well as topics which both physics and chemistry would claim, the two subjects are also linked in terms of the way chemistry assumes and applies topics from physics (Spice, 1975). An extreme view, that is sometimes heard, would be that 'all of biology can be reduced to chemistry, and all of chemistry can be reduced to physics'. Such slogans oversimplify a more complex relationship, and have led to considerable discussion in the literature (e.g. Scerri, 1991, 1993). The 'reduction' issue will be considered later in this paper. To avoid being distracted by such a debate, it is more useful to focus on the following principles (Taber, 2002a) which are assumed in this paper, and which are considered likely to be found reasonable by most readers:

- in preparing to teach a complex subject, such as chemistry, the teacher needs to undertake a 'content analysis' to determine the relationship between relevant concepts, and the logical order in which they should be presented;
- understanding of a topic at a more advanced level usually presumes an understanding of more fundamental ideas that may have been met earlier during less advanced levels (e.g. chemistry topics in upper secondary science build upon learning during lower secondary science);
- as part of the teacher's content analysis of a topic, this 'pre-requisite' knowledge which is assumed as a basis for introducing the new topic should be identified;
- as part of the process of teaching the more advanced topic the teacher needs to (a) check the presence and accuracy of the presumed pre-requisite knowledge among the learners, and (b) be explicit to the learners about the relevance of pre-requisite knowledge. Two of the ways that teaching can be ineffective are when pre-requisite knowledge is assumed that is not present (or is not accurate), and when learners do not recognise the relevance of the prior learning that the teacher is assuming provides the basis for new understandings (Taber, 2001b);
- when teaching certain areas of chemistry, some of the pre-requisite knowledge for understanding the topic may be drawn from physics topics as well as from less advanced chemistry topics.

Explanations in science and science education.

Science may be seen to be largely concerned with 'understanding' the world: understanding in terms of developing models and theories that can be used to explain and predict (Chalmers, 1982; Losee, 1993). Popper (1979: 191) suggested that "it is the aim of science to find satisfactory explanations, of whatever strikes us as being in need of explanation". A scientifically acceptable explanation would have certain qualities - for

example it would be expected to be internally consistent (lacking contradictions), logically coherent (providing a clear chain of cause and effect), and to refer to accepted scientific entities (electrons, forces, viruses etc., rather than fairies, ghosts or incantations).

One might therefore expect that 'explanation' would be a key feature of science education. Learning about science as a human cultural activity would seem to require the role of logic, modelling and developing explanations to be core themes. In addition it might be expected that the content of school and college science would heavily involve learning about the consensus models and explanations of modern science.

In practice it would seem that, until recently, these ideas have not been the subject of much research. Certainly psychological research in the Piagetian tradition has considered when learners might be capable of basic types of logical thought and this has influenced studies in science education (Bliss, 1995). However, it is only relatively recently that research has revealed that most school age learners have very simplistic and limited ideas of the roles of theories and models in science (Driver et al., 1996; Grosslight et al., 1991), and science educators have emphasised the teacher's role in teaching *about* as well as *with* models, theories and explanations (Gilbert, 1998; Gilbert et al., 1998; Ogborn et al., 1996).

The present author, and some of his colleagues, are interested in the way students understand the 'role' of explanation in science - something that we see as central to the scientific enterprise. We have been intrigued by the extent to which students rely on anthropomorphic explanations in chemistry (Taber & Watts, 1996), and in the points at which students reach the 'it just is' stage in developing scientific explanations (Watts & Taber, 1996), and we have found that the explanations constructed by students are often lacking in logical or conceptual underpinning (Taber & Watts, 2000; Gilbert, Taber & Watts, 2001).

In the present paper it will be shown that understanding patterns in ionisation energy - a topic taught in chemistry - depends upon explanations that apply ideas about force and electrical charge which are drawn from the domain of physics. These physical principles are part of the pre-requisite knowledge needed to make sense of the chemical topic.

Ionisation energy: a chemical topic applying physics knowledge

The topic of ionisation energy is studied in chemistry in the UK at the 'sixth form' or 'college' level, i.e. at the stage of education after completing compulsory schooling at age 16, and before moving on to University level study at age 18 or above. The standard qualification studied at this level is the 'advanced level' (A level) examination, normally studied over two years. The data reported in this paper were all obtained from students studying at this level for the A level or for the related AS qualification normally taken after one year of study (QCA, 2002). Students are expected to consider, and explain, patterns in standard molar ionisation energies (or enthalpies, but here the term energy will be used). As the models used in explanations invariably involve the consideration of single atoms, and as the definition commonly used refers to the removal of a mole of electrons from a mole of isolated gaseous (sic) atoms (e.g. Sharp, 1983) this paper will simply refer to 'ionisation energy', which will be taken to be measured and recorded as *per mole*, but discussed and explained at the proportionally smaller scale of *per atom*.

Although the process of ionisation might be seen as a more suitable topic for physics (when abstracted to the removal of a negatively charged electron from an atom with positively charged core), patterns of ionisation energy are seen as very significant *in chemistry*. The relative magnitudes of successive ionisation energies of an atom are related to the element's group in the periodic table (Pauling & Pauling, 1975), and the trends in first ionisation energies across periods or down groups are in turn related to key aspects of atomic

structure (albeit in terms of a relatively unsophisticated model of the atom, cf. Taber, 2002b). When Hess' law is used to explore the energetics of reactions there are often ionisation energy terms that need to be considered, so appreciating the relative sizes of ionisation energies certainly has practical significance when developing chemical explanations, such as about the feasibility of reactions.

So ionisation energy is very much seen as a 'chemistry topic', and at this level of study, when chemistry students first meet the concept, the target understanding would include:

1. that ionisation energies for an atom increase successively, and explaining this;
2. that the pattern of successive ionisation energies for an atom includes certain disproportionate increases, and explaining how this relates to the element's position in the periodic table;
3. that first ionisation energies decrease down a group of the periodic table, and explaining this;
4. that first ionisation energies across a period show a general trend to increase, and explaining this;
5. that the general trend of first ionisation energies to increase across a period is interrupted by (a) some reversals and (b) - in the higher periods - by regions of little change, and explaining these points.

At this level of study a relatively simple model of the atom can be used to explain these phenomena. Indeed, points 1-4 (and 5b) can be explained in terms of the type of atomic model commonly used in upper secondary school (e.g. 14-16 years) - and therefore familiar to the students from prior study - of an atom as a positive nucleus surrounded by concentric shells of electrons in planetary orbits.

Explaining point 5a requires a somewhat more sophisticated model where distinctions are made between the energy levels of orbitals having different azimuthal quantum numbers. Although point 5 is certainly important, and needs to be considered for a full exploration of student understanding of the topic, it involves understanding a model of the atom which is both inherently problematic (i.e. using hydrogenic orbitals to explain the structures of many-electron atoms), and which students at this level are still in the process of coming to terms with (Taber, 2002b).

The work discussed here will be limited to a consideration of students' ability to use the simpler 'concentric shells' model of the atom where the physical principles required are limited to simple electrostatic concepts. This model is clearly of restricted application, but nevertheless has currency in both science and the curriculum as a useful simplification (an important aspect of a model, cf. Gilbert, 1998) able to support scientific explanations, and - as we shall see - its application still provides significant challenges for students.

The basic electrostatic principles that may be used to discuss the atom as modelled in Figure 1, and which can be used to explain simple features of patterns in ionisation energies (i.e. points 1-4 above), are presented below. (The example of a sodium atom is used here because that was chosen as the focal example in the diagnostic instrument to be discussed later in this paper.)

It is worth noting that although the following account is largely based upon a single physical principle (Coulomb's law for the force between point charges), the complexity of even a relatively simple system such as that shown in Figure 1 makes a full analysis quite complicated for many 16-18 year old college level students. The decision to explain the

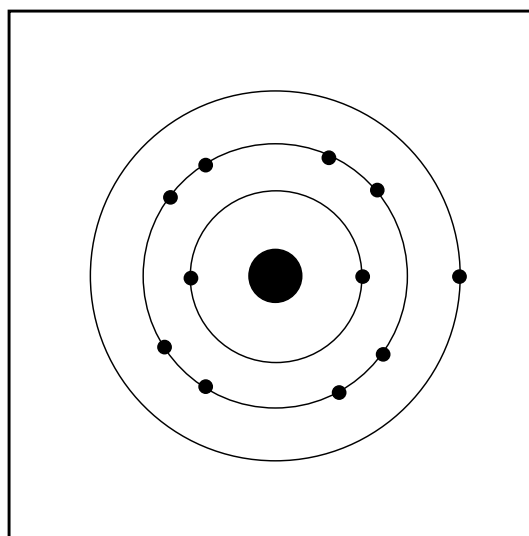


FIGURE 1: *A simple representation of the sodium atom.*

scientific model in the body of this paper (rather than relegate it to an appendix, or omit it as unnecessary in view of the likely readership of the paper) is a deliberate one.

It was stated above that in preparing to teach a complex subject, such as chemistry, the teacher needs to undertake a ‘content analysis’ to determine the relationship between relevant concepts (Herron et al, 1977; Kean, 1982), and the logical order in which they should be presented (Ausubel, 2000). Even, or perhaps especially, when a topic is very familiar to the teacher it can be easy to underestimate its complexity to the learner. This can lead to assuming too much prior learning, or not allowing enough time to process the complexity of new information in view of what is understood about the limitation of human cognitive processing, e.g. the severe limitation on working memory (Johnstone, 1991). By undertaking such a content analysis the teacher makes the ‘learning demands’ (Leach & Scott, 1995) explicit, and starts to appreciate the complexity of the material from ‘the learner’s resolution’ (Taber, 2002a).

The same logic suggests that such an analysis, to make our tacit assumptions of well-known science explicit, is also imperative when we are *researching* learners’ understanding of the science.

The sodium atom comprises of a positively charged nucleus (in this case with a charge of +11), and eleven negatively charged electrons arranged in three concentric shells around the nucleus. There is an attraction *between* the nucleus and an electron - the magnitude of this attractive force depends upon the charges (+11, -1) and the separation. This tells us that the force *between* the nucleus and an electron in the second shell will be larger than that *between* the nucleus and the outermost electron, but smaller than that *between* the nucleus and an innermost electron.

I have italicised the word *between* to emphasise how the interaction is mutual: the force acts on both charges. This is an example of the application of Newton’s third law, which is inherent in Coulomb’s law, that a force always act between bodies, and that both bodies experience force of equal magnitude along the same line of action, although anti-parallel - i.e. in opposite directions (see Figure 2).

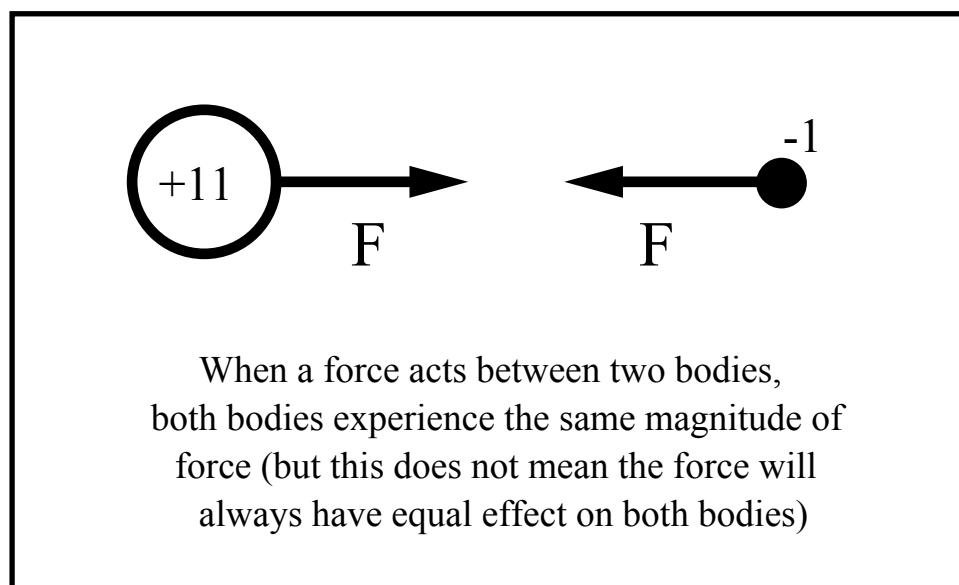


FIGURE 2: *Newton's 3rd law.*

Although electrons are all attracted to the nucleus, they are also repelled by each other - each electron is repelled by (and repels) each of the ten other electrons in this particular atom. The overall force acting on a particular electron in the atom will be the resultant, i.e. the vector sum, of the attraction to the nucleus and the repulsion by the other ten electrons - which are drawn as stationary bodies, but which are assumed to move with planetary-like orbitals in this simple model (Taber, 2001c).

Even for a relatively simple atom this provides a quite complex situation. Fortunately there is a simple principle we can apply to simplify the analysis. A spherical pattern of charge can - to an observer outside the sphere - be considered equivalent to the same charge placed at the central point. A shell of electrons has such a distribution of electron density.

So in Figure 1 the two electrons making up the first shell can be considered to have the same effect as two electrons placed at the nucleus, when 'observed' from outside the first shell, and the second shell of electrons can be considered to have the same effect as a charge of -8 placed at the nucleus, providing this is observed from outside that shell. It is worth just pointing out that although the notion of being 'outside' the shell is a straightforward one on the model being used in this analysis, this notion clearly becomes more problematic when more sophisticated models of the atom are used. All models have limits to their range of application and must be used with care - something that many learners in science classes do not fully appreciate (e.g. Driver et al., 1996; Grosslight et al, 1991), and something that teachers often fail to emphasise.

In chemistry this particular physics is used to develop new chemical concepts. Students may be taught that the inner electrons 'shield' the outermost electron from the effect of the nucleus. I would suggest that 'shield' is chemical shorthand for 'give rise to a repulsive interaction that partially cancels the nuclear attraction', although once the shorthand is accepted the notion of shielding may become reified and used without conscious awareness of its derivation (cf. Ogborn et al, 1996). Two other terms that are introduced are 'core charge' and 'effective nuclear charge'.

Core charge is a very useful concept (Taber, 2002c), which relies on the principles outlined above (that the total force on an electron depends on the vector sum of attraction and repulsions; and that the effect of the inner electrons is equivalent to their being located at the nucleus). This allows us to simplify a situation such as that shown in Figure 1: the outermost

electron may be considered to be effectively attracted to an atomic core of net charge (in this case, $+11-2-8=+1$).

The force attracting the electron to the nucleus can therefore be considered to depend upon only two factors in this case - the magnitude of the core charge, and the separation of the electron from the centre of the core, i.e. the nucleus.

I will not use the alternative term 'effective nuclear charge': because in my experience this is sometimes used as a synonym for core charge, but is used by other teachers to *also* include an allowance for the decreasing *effect* of the core charge with increasing separation. In my own view this latter use is confusing, and the potential ambiguity of the two meanings indicates core charge as the preferred term.

The first ionisation energy will therefore be the work done when removing an electron from the core (technically to infinity!) and so will be that needed to pull the electron away against the attraction from the core charge. This will not be an infinite quantity as the magnitude of the force falls rapidly with distance. Although the changing value of force implies that calculating the ionisation energy requires calculus, a qualitative understanding of the relative values in different cases is all that is required at the level being considered.

Unfortunately, the situation would be slightly more complex when considering the subsequent removal of a second electron for the atom shown in Figure 1. This is because whilst the electron is in the second ($n=2$, L) shell the other L shell electrons can not be considered to be part of the core, but their repulsions must be considered as significant; although once the ionisation process is underway the electron being removed will eventually be far enough away from the atomic residue for it to approximate to a point charge.

In other words the second electron is initially attracted by a core charge of $(+11-2=) +9$ and repelled by 7 other electrons which cannot be considered to be centred on the nucleus, but as it is pulled away from the rest of the system it can be considered to be being pulled away from a positive charge of $+2$ (i.e. even though the electrons remaining in the second shell do not make up a sphere of electron density centred on the nucleus, the distortion from this pattern is not significant once the electron is some distance from the remaining Na^{2+} ion).

For the removal of a third electron then the electron is initially attracted by a core charge of $(+11-2=) +9$ and repelled by 6 other electrons which cannot be considered to be centred on the nucleus, but as it is pulled away from the rest of the system it can be considered to be being pulled away from a positive charge of $+3$.

The *overall* effect here is that the second electron is being removed from a more positive charge than the first electron was, and the third electron is being removed from a more positive charge than the second electron. However, the student also has to consider how far the electron is from the nucleus before it is removed.

The second ionisation removes an electron from much closer to the nucleus than the first, as the electron is from the second ($n=2$, L) shell and not the third ($n=3$, M) shell. The third ionisation also involves an electron in the L shell, but in a sense this is not the 'same' L shell. The 'size' of the L shell (a meaningful concept in terms of the simple planetary model) depends upon the core charge attracting the electrons in the shell ($+11-2= +9$), and the amount of repulsion between electrons in the shell itself. A shell with seven electrons has less mutual repulsion than one with eight electrons in the same size shell: the L shell therefore becomes smaller as the core attracts these electrons closer against the mutual repulsion of less electrons. The outcome is that the third electron to be removed from the system is removed from closer to the nucleus than the second, even though they are nominally from the 'same' electron shell.

A student who appreciates these (sometimes quite subtle) points will have the potential to deduce key facts about the patterns in ionisation energies, and then to produce

explanations in terms of acceptable curriculum science. However, it is worth considering how complex the applications of these simple principles are when made explicit in the level of detail needed for appreciating the model being assumed.

Student understanding of ionisation energy

In view of the preceding analysis, and research that shows that learners often have alternative conceptions of force and related notions (e.g. Watts, 1983; Komporakis, 2002) it is not surprising that previous research has revealed that this is a topic where student understanding may be lacking (Taber, 1998a). Research based on interviews with students (in a Further Education College in the U.K.) revealed that learners often failed to appreciate basic electrostatic principles. So, for example, learners would not realise that the nucleus experienced a force attracting it to an electron as large as the force experienced by the electron. A common misunderstanding seems to be to assume that the force is smaller on the nucleus; although *some* learners feel there is no force on the nucleus, or even that it is repelled by the electrons!

The research also revealed two common alternative conceptions which were applied to make sense of ionisation energies. One of these was based on the notion that a full shell is especially desirable or stable. This notion, which forms the basis of a much wider alternative conceptual framework for making sense of chemistry at the molecular level (Taber, 1998b), takes the principle of a full shell being stable without regard to either (a) the reasons why such configurations often are stable, or (b) the particular context in which the principle is applied. So, for example, species such as Na^{7-} , C^{4+} , Cl^{11-} may be expected to be stable if they are considered to have full electron shells (Taber, 2002a).

The second common alternative conception was a notion of ‘conservation of force’ (Taber, 1998a), that is that a particular nucleus is able to provide a certain amount of force (depending upon its positive charge) which is then shared-out between the electrons present. From this perspective the removal of an electron allows the remaining electrons to experience a greater share of the nuclear force. Whilst being a very different sort of explanation to that derived above from electrostatics, this principle does often allow correct predictions to be made (successive ionisation energies do increase) and seems to have an intuitive attraction to many students. It seems reasonable to these students that if there are less electrons present, then they each receive more force from the nucleus.

A diagnostic instrument, ‘The Truth About Ionisation Energy’, that would allow the alternative conceptions identified to be readily diagnosed was developed and reported in the literature (Taber, 1999a). The instrument consisted of thirty statements to which students were asked to select ‘true’, ‘do not know’ or ‘false’. Following early pilot stages, the instrument was administered to a sample comprised of 110 students studying ‘A level’ chemistry in one English college. The results showed that among that sample there was substantial support for the alternative ideas identified in interviews.

AIMS OF THE PRESENT STUDY

The diagnostic instrument was designed with the following hypothesis in mind (Taber, 1999a): that *a significant proportion of A level chemistry students base their explanations of ionisation energies on the full shells explanatory principle and/or the conservation of force conception rather than on Coulombic electrostatics.*

This hypothesis refers to ‘A level chemistry students’ (typically 16-18 year olds), but the original use of the diagnostic instrument was in a single college. As the college offered,

and was well known for, one year re-sit courses (for students failing to obtain the desired end-of-course grades), such 'retake' students were strongly represented in the sample (making up five out of the seven teaching groups surveyed), whereas they make up a minority of the wider population of chemistry students at this level. It could be argued that students needing to re-sit the examinations *could be* more likely to hold alternative conceptions than the wider population.

Additionally, although the students studying at the college had previously attended a wide range of schools, they were all being taught A level chemistry in a single institution, and by the same small group of teachers. Furthermore, the diagnostic instrument had been derived following an interview-based study undertaken in *the same* college. It could be suggested that findings from the original study could largely reflect the particular features of teaching and learning in that specific environment. Although there is no particular reason to suspect that teaching in the college had unusual features encouraging the alternative conceptions identified, this is still a possibility that should be considered.

The study discussed here sought to answer the following question: *would a more heterogeneous group of students find statements based upon the identified alternative conceptions convincing?*

Data collection in the present study

During the Academic Year 2000-2001 the Royal Society of Chemistry (RSC) funded a project to develop and disseminate classroom materials for *Challenging Misconceptions in the Classroom* (Taber, 2001d). Most of the materials used in the project were written especially, but the Truth About Ionisation Energy diagnostic instrument was among a small number of existing instruments included.

This project invited participation from school and college teachers in the UK who wished to try-out and evaluate materials with their own classes. Those teachers expressing an interest were informed about the draft materials available (i.e. in terms of which topics and age groups) and were only sent materials they particularly requested.

Data for the particular study discussed here was collected from 17 institutions. The total number of learners responding was 334 (see appendix A), giving a mean group size around 20, but the actual number of students in each institution varied widely from a small sixth form group of 2 to a large college cohort of 98. The institutions were mostly schools but also included sixth form colleges and a further education college. Most of the institutions were state-funded, but some of the schools were 'independent' (i.e. private). The schools were spread widely across England, along both the North-South and the East-West directions. Although this sample is certainly a 'convenience' sample (Cohen et al., 2000), it is nonetheless a heterogeneous one.

Students were all taking courses leading to AS or A level chemistry (i.e. courses taken after completing school science, and required for university entrance, normally at 16-18 years of age), and were judged by their teachers to have covered the material needed to tackle the probe. Although the sample cannot be considered to be highly representative of the general population of AS/A level chemistry students, the involvement of learners from such a range of institutions provides a much more heterogeneous sample than the original research. While the self-selecting teachers could be considered to potentially have unrepresentative characteristics (perhaps a particular interest in the topic, perhaps an existing concern about their students' understanding of the topic, or perhaps a particular interest in educational research that might inform their teaching), it is unlikely that the composite sample of learners would have any particular idiosyncrasies.

Teachers did not report any major problems administering the probe, although some students apparently found dealing with thirty items on one page demanding - something that was taken into account when the materials were revised: the published version of the instrument included in the RSC classroom materials has only 20 items (Taber 2002d).

RESULTS

A small number of responses were ambiguous (e.g., both 'true' and 'false' selected for the same statement) or left blank, but - as in the initial study - this amounted only to about 1% of potential responses (124/10 020), which was considered acceptable. The number of unambiguous responses for each of the thirty items varied from 326/334 to 334/334. The number of students judging each statement as 'true', or 'false', or reporting they 'did not know' are given in appendix A. These figures have been converted to the nearest percentage point for the following discussions.

Applying Coulombic principles

Two thirds of the respondents (67%) recognised that 'each proton in the nucleus attracts all the electrons' (item 17), but a substantial minority (27%) agreed with the statement that 'each proton in the nucleus attracts one electron' (item 4).

Most respondents seemed to appreciate that the magnitude of electrical attraction decreased as distance increased. Only a small proportion (6%) of the respondents agreed that 'all electrons are attracted to the nucleus equally' (item 3).

A majority (62%) accepted that 'the nucleus is attracted towards the outermost electron less than it is attracted towards the other electrons' (item 25). Although a significant minority (29%) disagreed with this principle, a large majority (84%) recognised the related point that 'after the atom is ionised, it then requires more energy to remove a second electron because the second electron is nearer the nucleus' (item 2).

It may be relevant here that item 25 was worded in terms of the force acting *on* the nucleus. Although the force acts upon the nucleus and electron symmetrically, this is not recognised by some students. So a quarter of respondents (26%) agreed that 'the nucleus is not attracted to the electrons' (item 8). Indeed half (50%) of the respondents were convinced by the statement 'electrons do not fall into the nucleus as the force attracting the electrons towards the nucleus is balanced by the force *repelling* the nucleus from the electrons' (item 15).

Six items asked students about the relative magnitudes of the force acting between the nucleus and an inner (items 1, 14, 27) or an outer (items 10, 22, 29) electron. It is interesting that the results suggest that some respondents must have agreed with contradictory responses (a point taken up in the discussion), but in both cases the strongest support was for the statement suggesting that the electron experienced a greater force: 59% for 'the force pulling the outermost electron towards the nucleus is greater than the force pulling the nucleus towards the outermost electron' (item 10) and 67% for 'the force on an innermost electron from the nucleus is greater than the force on the nucleus from an innermost electron' (item 1).

An alternative electrostatic principle

A number of the items (7, 13, 19, 21, 23, 24) in the instrument were designed to reflect the 'conservation of force' conception (Taber, 1998a) that had been identified as an

explanatory principle applied by students in interviews. In each case, in the RSC data, there was a majority response reflecting this alternative conception.

So almost three quarters of the sample (72%) agreed that ‘the eleven protons in the nucleus give rise to a certain amount of attractive force that is available to be shared between the electrons’ (item 13) and over half (55%) agreed that ‘if one electron was removed from the atom the other electrons will each receive part of its attraction from the nucleus’ (item 7). A similar proportion of the respondents (57%) agreed that ‘the third ionisation energy is greater than the second as there are less electrons in the shell to share the attraction from the nucleus.’ (item 21).

Three-fifths of the respondents (61%) agreed with the statement ‘after the atom is ionised, it then requires more energy to remove a second electron because once the first electron is removed the remaining electrons receive an extra share of the attraction from the nucleus’ (item 24). There were a number of items which offered explanations for this increase in ionisation energy (items 2, 9, 16, 20, 24, 28), five of which were correct according to the scientific model. The ‘alternative’ explanation in terms of sharing-out of nuclear charge was more popular among respondents than three of the technically correct statements: those in terms of the second electron (i) being removed from a lower energy level (item 16, 59%), (ii) experiencing a greater core charge (item 28, 49%), and (iii) being removed from a more positive species (item 20, 47%).

An alternative notion of stability

The whole notion of ‘ionisation *energy*’ is only meaningful because the process of removing a negatively charged electron from the attraction of a positively charged atomic core is an endothermic one. It is reassuring, then, that nearly all of the respondents (98%) recognised the truth of the statement that ‘energy is required to remove an electron from the atom’ (item 6). However, despite this near unanimity, a modest proportion (14%) of the respondents nevertheless agreed that ‘the atom will spontaneously lose an electron to become stable’ (item 11).

This finding appears to relate to the understanding of ‘stable’ which respondents used to judge statements, which seems to be closely linked to ideas of octet configurations, or full shells. The Na^+ ion has an electronic configuration which is usually considered in ‘chemical contexts’ (see the discussion) to be stable. Research has found that some students argue that electrons cannot be removed from such a stable configuration, even though they may have studied patterns in successive ionisation energies where this is clearly happening (Taber, 1999a). Among the respondents in the RSC project, almost a quarter (24%) agreed that ‘only one electron can be removed from the atom, as it then has a stable electronic configuration’ (item 12).

Indeed, even though a vast majority of the students responding knew energy was required to ionise the atom only 7% agreed that ‘the atom would be less stable if it ‘lost’ an electron’ (item 26), whilst almost four-fifths (79%) agreed that ‘the atom would be more stable if it ‘lost’ an electron’ (item 5).

One of the disadvantages of survey-type methods is that there is no opportunity to follow up responses to ask what the students understood by the terms used in the questions, and it could be suggested that ‘stable’ could be used by some students as nothing more than a label for the types of electronic structures commonly referred to as stable in chemistry. Yet this would not explain why just over half (52%) of the respondents agreed that ‘if the outermost electron is removed from the atom it will not return because there will be a stable electronic configuration’ (item 30). In this case, at least, the notion of stability used over-

rides electrostatic considerations. Indeed four-fifths (83%) of the respondents agreed that ‘the atom would become stable if it either lost one electron or gained seven electrons’ (item 18). The Na^{7-} ion would have an octet of electrons in its outer-shell, and it seems that *this* criterion of stability carries more weight than the electrostatic instability of the highly charged (metal) anion!

DISCUSSION

Interpreting the results

One should take care in reading too much significance into the precise percentages quoted for supporting the various statements. A number of factors indicate caution. For one thing the self-selecting nature of the institutions involved prevents this from being a representative survey, even within the U.K. context. The instrument used was (necessarily perhaps) wordy, including some items making high language demands on the respondents. Perhaps most significantly the use of thirty items, including some very similar to others, could have led to both a degree of fatigue and confusion - although the availability of a ‘do not know’ option provided a safeguard against students feeling pressurised into giving a definitive answer where they could not make sense of an item, or were unsure whether a statement was true or false.

One particular point that could be considered to throw doubt upon the validity of the instrument is that it is quite clear that at least some of the items elicited responses that were mutually contradictory (something that was also found in the original use of the instrument, Taber, 1999a). If it is considered that students will hold a single coherent explanatory framework for a topic such as ionisation energy then it would be expected that they should not agree with two contrary statements.

The students in the original interview studies which preceded and inspired the development of the instrument do provide some clues to why such a pattern of responses may be obtained. At this level students may be in the process of ‘transition’ between models (Taber, 1999b) and operating with manifold conceptions (Taber, 2000a, 2001e). Similar situations have been found in other studies where science students’ conceptual development has been explored in depth (e.g. Harrison & Treagust, 2000; Petri & Niedderer, 1998). In such a situation it is quite likely that there would be a tendency to judge as ‘true’ items which are consistent with one *or* other of the alternative conceptions considered relevant to the context, even though this means agreeing with apparently contradictory statements.

In the diagnostic instrument there were six statements offering possible explanations of why the second ionisation energy was greater than the first, and five of these different statements were consistent with the curriculum model. It was quite appropriate for respondents to select five ‘different’ explanations for this phenomenon, and it is only from the perspective of the model used to understand and teach this topic that we can make judgements about whether statements that respondents may have selected *are* contradictory.

The outcome of this caveat is that we should interpret the percentage figures as reflecting the statements which students *found convincing* because they were consistent with *one of* their available ways of thinking about the example, rather than as reflecting statements showing *the* way the students think about the example. However, even from this less severe perspective, the findings indicate a situation of some concern.

Implications for teaching

In general, most students seemed to be aware of the basic electrostatic principles that opposite charges attract and that increased separation of charges leads to a reduced force between them.

The respondents were less convinced by the basic physical notion that forces act with equal magnitude and opposite direction on interacting bodies, and there was considerable support for the idea of the nucleus exerting more force on the electron than vice versa. This perhaps shows a failure to clearly separate the notion of force, from its effect. Now it seems fair to ask if the respondents should have been expected to be able to answer questions about the force acting on the nucleus, as it is not explicitly drawn upon in explanations of ionisation energy. It is however considered of interest that there was substantial agreement with both the idea that the nucleus would not be attracted to electrons, and indeed that the electrons were pushing on the nucleus. (The latter item was partly inspired by an interviewee who suggested that nuclear stability could be due to “the forces from the outer shells...pushing” the protons together!) Although chemistry students may be excused from appreciating how forces act with equal magnitude on both charged bodies, they would be expected to know that a positive charge should always be attracted to a negative charge.

Although understanding patterns in ionisation energy requires the application of some physics, *aspects of* Coulombic electrostatics, it would seem that some chemistry teachers are content to abstract out those aspects which are directly used in the chemical arguments (e.g., *the nucleus attracts the electron*, cf. there is *a force between* the nucleus and the electron) without referring to the basic physical principles *per se* (i.e. $F \propto q_1 q_2 / r^2$). This was certainly a point raised by some of the teachers in the RSC project in their own feedback. One suggested that the instrument “addresses ideas not specifically taught, i.e. electron attracting nucleus and equality of force” and another suggested that the instrument “seemed to be a close study of A level Physics electrostatic attraction”. Another did not like the use of the term ‘magnitude’ (very common in physics teaching, but not judged by this author as a specialised *physics* term) to refer to the size of a force,

“*Force magnitude* is not a phrase I have encountered specifically in current A level syllabuses ‘Forces of attraction’ is more common.”

This is all very well, but these findings from the RSC project do suggest that students do not only ignore those aspects of the physics which are not immediately needed, but they also commonly adopt an *alternative* principle of electrostatics, that the nuclear attraction is shared between the electrons. This belief in *sharing-out of*, or *conservation of*, nuclear force is a completely aphysical principle which is clearly contradicted by Coulomb’s law: the force between two charges depends upon the magnitudes of the two charges and their separation - there is no reference to whatever other charges may happen to be in the vicinity.

Directions for future research

As with most research this study provides indications of possibly fruitful avenues for future research. One direction concerns aspects of the chemistry topic of ionisation energy not considered in the present study. The diagnostic instrument used in this study discussed one example (the ionisation of a sodium atom) where a simple ‘concentric shells’ model of electronic structure was a sufficient basis for explaining the phenomena. Yet students at this level are also expected to be able to use a more sophisticated model of the atom in terms of

orbitals and sub-shells in order to explain other, more subtle, features of patterns in ionisation energies. It is known that these models present considerable difficulties for college-level students (Taber, 2002b).

The instrument used in the research reported here derived from in-depth studies of student thinking which identified features of the way individuals understood and explained phenomena such as ionisation. The purpose of the present study was to find out whether a significant proportion of a heterogeneous sample of A level chemistry students based their explanations of ionisation energies on the full shells explanatory principle and/or the conservation of force conception rather than on Coulombic electrostatics.

Basing items upon prior interviews is one way of ensuring that the options in such research tools are able to offer authentic reflections of student thinking. A similar approach is to first offer open-ended written questions, and to select common responses as the distractors in multiple choice tests (Schmidt & Beine, 1992). Schmidt's research group have also used distractors which have been commonly chosen in public examinations, and then included them as options in multiple choice items where the respondents are also asked to explain their choices (e.g. Schmidt, 1997). An alternative approach asks students to select both an answer to a question, and also the justification from options provided (Tan & Treagust, 1999).

To probe student thinking about the additional features of ionisation energy not explored in this study, Tan is developing a new instrument with a more comprehensive coverage of the topic. Tan is using his new instrument to explore the thinking of students studying at a comparable level in the Singapore system. The format is a justification multiple choice instrument, which presents statements for students to judge as true or false, but *also* asks them to give a reason for their choice.

More research would certainly be useful to explore *other* issues raised in the present study in more depth. In view of notions of nuclear force being shared-out, it would be interesting to know, for example, if students believe an isolated nucleus gives rise to any force.

A distinct aspect of the present study worthy of further enquiry concerns the notion of 'chemical shorthand'. It seems ideas which originate from justifiable chains of logic may be developed into heuristics which come to be used uncritically. The example of 'shielding' was given in the introduction. It was suggested above that 'shield' is chemical shorthand for 'give rise to a repulsive interaction that partially cancels the nuclear attraction', although once the shorthand is accepted the notion of shielding may become reified and used without conscious awareness of its derivation.

I recently had an extended discussion with a graduate trainee chemistry teacher who was convinced that the outer electron in a lithium atom was attracted less to the nucleus than the inner electrons in part because of the greater separation, but in part because of the shielding effect of the first shell of electrons. He did not seem to see the shielding as a matter of repulsion which could cancel some of the attraction, but as a more literal 'shield' which reduced the effect of the nucleus itself. Whilst such anecdotal evidence should not be given much weight in itself, it does perhaps suggest a useful avenue for further research. In the present study the notions of sharing-out of nuclear attraction, and the absolute stability of octet structures ('full outer shells') seem to be heuristics which are used as shorthand chemical rules-of-thumb, standing in the place of explanations derived from physical principles.

It is known that complex explanations involving several causes are not readily invoked by learners (Driver et al, 1996). One possible interpretation of the results discussed here is that students are adopting a more holistic approach in their analyses, and may have difficulty ignoring the effects of the other electrons present on the *net* force experienced by

an electron. The sharing-out heuristic may be a useful way for them to short-circuit the complications of the type of analysis presented in the introduction.

Insights into the relationship between physics and chemistry teaching

One possible interpretation of the data reported here is that the decision of many chemistry teachers to provide qualitative explanations which call *selectively* upon the physical principles leaves open the opportunity for students to develop an alternative electrostatic principle which sees (i) the nuclear charge (and not the nucleus-electron interaction) as the source of force, (ii) the size of the nuclear charge as the sole determinant of the total amount of force available to hold electrons, and (iii) the number of electrons as determining the share of the attraction that each electron receives.

Now this is clearly an incorrect model from a physical perspective, but it might be asked if this really matters. If the ‘conservation of force’ principle provides a useful heuristic that allows students to remember and predict what is happening during successive ionisations then it could be suggested that its aphysical nature is irrelevant.

This would certainly be a possible position that one might take from within an (insular) context of teaching and learning chemistry. However, from an alternative perspective, where we might see chemistry as one component of a science curriculum, and wish learners to appreciate how the different sciences fit together, we would not wish to sacrifice physical correctness for a quick chemical ‘fix’. One might draw an analogy with the irritation some chemistry teachers feel when their students learn in biology about how the role of ATP in metabolism is based upon its having an ‘energy-rich phosphate bond’ which stores energy that is released when the bond is broken (Hapkiewicz, 1991).

The present author’s instinct is that simplifications are necessary when teaching abstract and complex topics, but scientific falsehoods should not be tolerated (Taber, 2000b). If however, as some research suggests, students compartmentalise their knowledge according to the discipline structure of the curriculum as a coping strategy (Taber, 1998a), then this may not be such a straightforward discussion. As one chemistry teacher reported when providing feedback on the diagnostic instrument: “questions referring to ‘forces’ were confusing (i.e. it made them think hard!)”

The notion of ‘chemical stability’ provides a further context to explore this issue. Stability is a relative term which only becomes meaningful in a particular context. For example, a carbon-carbon double bond has greater bond energy than a carbon-carbon single bond, and so could be said to be more stable than the single bond. Yet the pi component of the double bond is readily ‘attacked’ and ruptured during addition reactions - which would suggest it is an unstable feature. The term ‘stable’ needs to be qualified by an indication of ‘with respect to...’

In most chemically likely environments Na^+ is a relatively stable species, and learners would be advised to expect sodium to commonly be found in the form of Na^+ rather than Na atoms. However, ionisation energy is defined in terms of isolated atoms and so judgements of stability need to consider how stable the ion is compared with the atom in the absence of the net electrostatic field of a metallic lattice, a solvent sheath of water molecules or a surrounding set of counter-ions. In this state the atom is more stable than the separated Na^+ ion and electron. The atom will not spontaneously ionise, but the negative electron and positive cation *would* spontaneously attract each other and combine to form an atom. In this situation electrical neutrality is a more significant criterion of stability than having a full shell, something that is not recognised by many students. As one teacher piloting the

instrument for the RSC project reported “the main misconceptions seemed to be the assumption that a stable electron configuration implied a stable particle”.

The respondents in the RSC project have developed a notion of ‘chemical stability’ which is usually a useful guide, but has become divorced from the basic underlying (physical) principles. That so many students seem to judge the Na^{7-} anion more stable than the sodium atom underlines just how significant the notions of octets of electrons and full shells have become for many students at this level. Ironically the Na^{7-} species is highly unstable, and could only be stabilised by the imposition of a very significant external electrical field - something that a physicist could presumably arrange, but which is most unlikely to occur in any feasible chemical environment a chemist might be able to synthesise. One of the teachers piloting the materials commented that, since seeing the students’ responses, “I have certainly been *much more* careful not to imply (not by my design!) that the very *raison d’être* to lose electrons is merely to obtain noble gas structures”.

When the original instrument was administered to the sample of 110 college students (Taber, 1999a) the levels of support for some incorrect statements were so high that there was some suspicion that respondents might be misreading or misunderstanding the statements. Three quarters of that original sample (75% cf. 79% in the present study) agreed that ‘the atom would be more stable if it ‘lost’ an electron’ and over half (56% cf. 52%) of the students agreed that ‘if the outermost electron is removed from the atom it will not return because there will be a stable electronic configuration’; whilst over four-fifths (83% cf. 83%) of the sample agreed that ‘the atom would become stable if it either lost one electron or gained seven electrons’. However the writing of new instruments to explore these specific points (‘stability and reactivity’ and ‘chemical stability’, Taber, 2002d) reinforced the original findings. It seems that, as the present study suggests, many students do feel that *any* species with an octet or full shell of electrons - Na^{7-} , C^{4+} , C^{4-} , Be^{6-} , Cl^{11-} (Taber, 2002a) - must be more stable than the corresponding neutral atom.

Again it would be possible to argue that the results obtained here are little more than an artefact of the questions asked. In chemical contexts the octet rule heuristic is very useful, and asking students about isolated atoms and ions has little to do with most chemical systems. Whilst this is a defensible position, we do currently include the topic of ionisation energy in chemistry courses, and indeed often abstractly reinterpret many reactions as a set of such isolated steps (e.g. the Born-Haber cycle). Another of the teachers piloting the material commented on the debriefing of the group of students,

“We had quite a detailed talk about so-called stable configurations and energy levels. They found the idea that Na^+ and e^- is less stable than Na quite confusing but eventually helpful, and the inputting of Ionisation Energy helped them see this. They felt more comfortable when considering ‘real’ reactions other than the reaction $\text{Na}_{(\text{g})} \rightarrow \text{Na}^+_{(\text{g})} + \text{e}^-$.”

There are many concepts which we would identify as ‘chemical’, such as neutralisation, oxidation, aromaticity, halogen, and so forth. On a simple view that is sometimes put - that all of chemistry is in principle reducible to physics - it might be possible to explain and redefine such concepts in terms of basic physical principles. But even if this were to prove possible (and a chemical Bertrand Russell was to take up the challenge) it may prove a pointless task. Such concepts do mental work for us as category labels, allowing us to treat complex ideas economically and to recognise myriad novel instances as if familiar examples. As human beings we suffer severe limitations on our ability to process complex

information (e.g. Johnstone, 1989, 2000; Taber 2000c) and such conceptual strategies are essential to our making sense of the world.

However this also means that we are in danger of forgetting the derivation of our new chemical concepts, and so of losing sight of the more fundamental principles upon which they are based. So as teachers we may offer a limited discussion of the electrostatics behind even a simple planetary model of the atom, that allows students to invent their own alternative electrostatic principles, or we may through our classroom discourse bring new entities into being (Ogborn et al. 1996), such as ‘chemical stability’, without making explicit the range of contexts over which such a construct has validity.

CONCLUSIONS

There are two types of conclusion I would wish to draw from this study. At one level the findings are clear: it was common for 16-18 year old students in this UK sample to have limited understanding of the electrostatic principles underlying the topic of ionisation energy, and many of the students agreed with statements based upon alternative explanatory principles of the sharing-out of nuclear force, and the inherent stability of any species with octet electron structures. It would seem that the topic of ionisation energy is not well understood by UK students at this level.

The wider implications are less clear cut. Students develop technically incorrect heuristics which generally give accurate predictions (the conservation of force conception) and notions of stability which work well within most likely chemical contexts. Despite having some utility, these ideas are fundamentally unsound. If we feel that chemistry should be a relatively self-contained discipline (at least within the curriculum), then we could perhaps tolerate this situation. Students seem to find such ideas acceptable and do not seem to need to link them with any underlying physics.

It may help students to allow them to keep their chemistry and physics knowledge safely compartmentalised, and the ‘greater order’ which might seem to offer simplification to the expert may just be an additional burden to the novice learner. However, the present author has some unease about such a position.

It was suggested in the introduction that a central feature of science is the quest to develop explanations. If the essence of science could be reduced to anything, then ‘providing answers to ‘why’ questions’ (i.e. explanations) would seem to be a worthy candidate. Yet research is suggesting that this is an area where science education is having limited success, and where more research, into both the current situation and developing best practice, should be a priority. In the present study we find college level students convinced by explanations based on principles, such as sharing out of nuclear force, which have no conceptual underpinning from consensus science, and applying chemical notions such as the stability of octets of electrons without any sense of their range of application.

Benfey (1982) asked how the concepts of chemistry should be characterised: ‘as mechanical, organicist, magical or what?’ It might be suggested that when students fail to apply physical principles to their chemistry in such a stripped-down context as ionisation energy, then they are using chemical concepts without any understanding of their derivation - chemical concepts that must seem to them as much magical as scientific.

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APPENDIX: RESPONSES TO THE DIAGNOSTIC PROBE IN THE RSC TRIAL

<i>Item statement</i>	T	D	F	•
1 The force on an innermost electron from the nucleus is greater than the force on the nucleus from an innermost electron.	224	21	87	332
2 After the atom is ionised, it then requires more energy to remove a second electron because the second electron is nearer the nucleus.	277	2	52	331
3 All electrons are attracted to the nucleus equally.	20	5	308	333
4 Each proton in the nucleus attracts one electron.	91	33	207	331
5 The atom would be more stable if it 'lost' an electron.	264	8	61	333
6 Energy is required to remove an electron from the atom.	326	1	5	332
7 If one electron was removed from the atom the other electrons will each receive part of its attraction from the nucleus.	183	49	99	331
8 The nucleus is not attracted to the electrons.	88	26	220	334
9 After the atom is ionised, it then requires more energy to remove a second electron because the second electron experiences less shielding from the nucleus.	206	10	117	333
10 The force pulling the outermost electron towards the nucleus is greater than the force pulling the nucleus towards the outermost electron.	195	37	99	331
11 The atom will spontaneously lose an electron to become stable.	46	19	269	334
12 Only one electron can be removed from the atom, as it then has a stable electronic configuration.	80	5	246	331
13 The eleven protons in the nucleus give rise to a certain amount of attractive force that is available to be shared between the electrons.	235	45	48	328
14 The force on an innermost electron from the nucleus is equal to the force on the nucleus from an innermost electron.	126	45	159	330
15 Electrons do not fall into the nucleus as the force attracting the electrons towards the nucleus is balanced by the force repelling the nucleus from the electrons.	166	41	122	329
16 After the atom is ionised, it then requires more energy to remove a second electron because the second electron is in a lower energy level.	195	23	110	328
17 Each proton in the nucleus attracts all the electrons.	224	39	69	332
18 The atom would become stable if it either lost one electron or gained seven electrons.	274	10	46	330
19 The force attracting the electrons in the first shell towards the nucleus would be much greater if the other two shells of electrons were removed.	182	35	110	327
20 After the atom is ionised, it then requires more energy to remove a second electron because it would be removed from a positive species.	152	82	92	326
21 The third ionisation energy is greater than the second as there are less electrons in the shell to share the attraction from the nucleus.	188	19	122	329
22 The force pulling the outermost electron towards the nucleus is smaller than the force pulling the nucleus towards the outermost electron.	70	67	192	329
23 The force attracting the electrons in the first shell towards the nucleus would not change if the other two shells of electrons were removed.	142	18	169	329
24 After the atom is ionised, it then requires more energy to remove a second electron because once the first electron is removed the remaining electrons receive an extra share of the attraction from the nucleus.	201	27	100	328
25 The nucleus is attracted towards the outermost electron less than it is attracted towards the other electrons.	205	29	96	330
26 The atom would be less stable if it 'lost' an electron.	24	3	300	327
27 The force on an innermost electron from the nucleus is less than the force on the nucleus from an innermost electron.	55	44	226	325
28 After the atom is ionised, it then requires more energy to remove a second electron because it experiences a greater core charge than the first.	160	73	95	328
29 The force pulling the outermost electron towards the nucleus is equal to the force pulling the nucleus towards the outermost electron.	164	34	131	329
30 If the outermost electron is removed from the atom it will not return because there will be a stable electronic configuration.	170	22	134	326

T: number of respondents selecting 'true';

D: number of respondents selecting 'do not know';

F: number of respondents selecting 'false';

• sub-total (/334) of unambiguous responses to the item.

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