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College students' conceptions of chemical stability: The widespread adoption of a heuristic rule out of context and beyond its range of application

Abstract.

This paper reports evidence that learners commonly develop a notion of chemical stability that, whilst drawing upon ideas taught in the curriculum, is nevertheless inconsistent with basic scientific principles. A series of related small-scale studies show that many college-level students consider that a chemical species with an octet structure, or a full outer shell, will necessarily be more stable than a related species without such an electronic configuration. Whilst this finding is in itself consistent with previous research, the present paper shows how students commonly apply this criterion without consideration of chemical context, or other significant factors such as net charge. Species that would seem highly unstable and non-viable from chemical considerations, such as Na^{7-}, C^{4+} *and even* Cl^{11-}, *are commonly judged as being stable. This research shows that many college level students are privileging a simple heuristic (species with full outer shells will be stable) when asked about the stability of chemical species at the submicroscopic level, to the exclusion of more pertinent considerations. Some students will even judge an atom in an excited state as more stable than when in the ground state, when an electron is promoted from an inner shell to 'fill' the outer shell. It is suggested that the apparently widespread adoption of a perspective that is so odds with the science in the curriculum is highly significant for the teaching of chemistry, and indicates the need for more detailed studies of how such thinking develops and can be challenged.*

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College students' conceptions of chemical stability: The widespread adoption of a heuristic rule out of context and beyond its range of application

Introduction: chemical reactions in school science

In school science and college chemistry, students meet many examples of chemical changes, i.e. reactions – "the processes that convert substances into other substances", (Pauling & Pauling, 1975: 13), where specific reactants give particular products. At secondary school level it is normal to focus almost exclusively on reactions that may be considered to effectively 'go to completion' (van Driel, de Vos, & Verdonk, 1990). Students will find that some reactions that they can conceive of occur (under conditions that can be produced in the school laboratory), whilst others – which would satisfy the same rules of conservation, valency etc. – do not. Certain substances (e.g. potassium) will be labelled as being '*reactive*' whilst others (e.g. silver) will be described as '*unreactive*'. The noble gases, still sometimes referred to as the '*inert*' gases, may be described as having atoms with '*stable*' electronic configurations. However, the conceptual tools necessary to appreciate why some chemical systems are more stable than others are not usually taught at this introductory level.

A number of studies that have explored student thinking about chemical change have found major deficiencies in understanding. Learners may not have good understanding of prerequisite concepts such as chemical substance (Ahtee & Varjola, 1998; Hesse & Anderson, 1992; Johnson, 2000); or of what is changed, and what is conserved during chemical processes (Briggs and Holding, 1986), and how these differ from physical changes (Watson & Dillon, 1996; Ahtee & Varjola, 1998; Hesse & Anderson, 1992; Stavridou & Solomonidou, 1989; Taber, 2002a); and they may set inappropriate restrictions on what qualifies as a reaction (Stavridou & Solomonidou, 1998; Cavallo, McNeely & Marek, 2003). Learners may fail to use a viable particle model (Anderson, 1986; Hesse, & Anderson, 1992; Watson, Prieto & Dillon, 1997; Johnson, 1998; Harrison & Treagust, 2002), where linking these models with macroscopic phenomena is a long-standing concern in chemical education (Jensen, 1995; Johnstone, 2000; Harrsion & Treagust, 2002; Gilbert & Treagust, in

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preparation). Some of these weaknesses continue through secondary school, and have been found among college level students (Ahtee & Varjola, 1998; Barker and Millar, 1999; Solsona, Izquierdo & de Jong, 2003).

An 'explanatory vacuum' at school level

Chemical changes are commonly said to be feasible when the products are 'more stable' than the reactants. Stability is a thermodynamic concept, which relates to the tendency of the state of a chemical system to change spontaneously (i.e. without external influence). Such changes may not happen quickly, so that a diamond is unstable under conditions at the earth's surface, and would, eventually, spontaneously change into a different allotropic form of carbon. However, diamonds are inert, so the typical timescale for such a spontaneous change is – in human terms – extremely large. Diamonds form deep beneath the earth's surface where diamond is the stable allotrope, under rather different temperatures and pressures to those found at the surface. A chemical judgment of stability then (a) is distinguished from kinetic concerns, and (b) is relative, and is not absolute for a particular substance or chemical species.

Reporting that a particular reaction occurs because the products are more stable than the reactants is in itself a fairly limited form of explanation (Taber & Watts, 2000). Understanding why some particular chemical system is more stable than another under certain conditions is often a complex issue. In a *college level* (Senior High School) course these questions will be considered in terms of such concepts as bond enthalpies, entropy, free energy, ionisation energies and so forth. These ideas are not introduced at school level, where the question of why some reactions occur, and others do not, is not normally treated in any depth. Chemical stability, then, is a key concept in chemistry, but one that is only *explained* at college level, although it will already have been met in secondary school.

The octet heuristic and octet thinking

One aspect of chemical stability that *is* met at secondary level is the very useful heuristic of the octet rule (Jensen, 1984). Nearly all of the stable chemical species (atoms, molecules, ions) discussed at secondary level can be considered to obey the

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octet rule, i.e. with octets of electrons in their outer shells, except for hydrogen and helium atoms which are stable with 'full' shells of two electrons. This is a very useful 'rule-of-thumb' that enables students to predict which simple ions are likely to be commonly found (e.g. Na^+ and Be^{++}, but not Na^{++} or Be^-), and the likely formula of simple compounds (e.g. CO_2 and NH_3, rather than CO_4 and NH_2). Despite its usefulness, the octet rule has a limited range of application. There are many compounds that may later be met in *college level* chemistry that do not fit with the rule: CO, PCl_5, $AlCl_3$, XeF_4, and so on.

It is important for students to realise that the octet rule (even where it applies) only offers a heuristic for predicting feasible ions and molecules. Even within its range of application, it does not help us predict whether a substance is likely to react. As pointed out above, stability is a *relative* term. So the methane molecule, CH_4, fits the octet rule criterion for stability, but that does not 'protect' methane from reacting with oxygen. This is a point that many learners may miss: students will 'explain' a reaction occurring to give 'octets' or 'full outer shells' of electrons when the species present in reactants and products all 'obey' the rule to an equal extent (Taber, 2002a). The octet rule forms the basis of a common and wide-ranging explanatory framework that many students develop (with individual variations) during upper secondary courses, and then apply widely in chemistry at college level (Taber, 1998).

Many learners see the driving force for bond formation, and indeed chemical change itself, to be tied to the idea of atoms having 'octet', or 'noble gas', or 'full outer shell' electronic structures - terms which often seem to be used synonymously by students (Taber, 1998), although neon is the only noble gas element to have a full outer shell of eight electrons – being stable. In this paper this explanatory principle, however phrased, will be referred to as 'octet thinking' for economy.

Student ideas about chemical stability

When A level students (16-19 year olds in England, usually of above average ability), studying chemistry in a Further Education college were presented with true/false items relating to the concept area of ionisation energy, over four-fifth (91/110) agreed with a statement "the [sodium] atom would become stable if it either lost one electron

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or gained seven electrons" (Taber, 2000). A subsequent study based on a larger, more heterogeneous sample made up of students from 17 UK institutions found a very similar proportion of respondents (274/330) agreed with the statement (Taber, 2003a).

A surprising finding

If students were reading the probe item as intended then the responses suggested that a substantial number thought that Na was less stable than Na^{7-}, even though:

a) students learn at secondary school that metals form cations,
b) the Na^{+} ion is the only sodium ion present in any substance studied in school or college chemistry, and
c) students at this level were unlikely to have come across *any* substance including ions with a greater net charge than three: (Al^{3+}, N^{3-} perhaps).

A new probe (Taber, 2000) was prepared to check on any ambiguity that might be read into the wording of the item.

A probe to explore student thinking about chemical stability

This original version of the Chemical Stability Probe (Taber, 2000) was administered to two A level Chemistry groups in the same institution where the ionisation energy probe had been used (students who had already studied relevant topics, e.g. ionisation energies, at A level standard; students just commencing A level studies).

Figure 1: Diagram presented in the original probe (Taber, 2000)

The original version of the Chemical Stability Probe (as briefly reported in Taber, 2000: 479-480) consisted of 3 closed questions asking students to compare the species in pairs (i.e. Na^{+} cf. Na•; Na• cf. Na^{7-}; Na^{7-} cf. Na^{+}), and one open question asking respondents to "explain the reasons for your answers to questions 1-3". A diagram at the top of the page showed the species, labelled A, B and C (see Figure 1). The choice of type of diagram included in this and other probes reported in this paper is considered in the Methodology section below. In each comparison there were four

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options: that the first species in the pair was more stable, equally stable, or less stable than the second, and a 'do not know' option (for format of probe, see Taber, 2000: Appendix 3). The validity of asking students to make decontextualised comparisons in this way is considered in the Discussion section of the paper.

The responses to the three closed questions from the two groups (previously reported in outline, in Taber 2000: 479-480 and Taber, 2002a: 103) are given in full in tables 1 and 2:

Table 1: Judgements of stability from an A level group having studied relevant topics

Table 2: Judgements of stability from a group of students commencing A level studies

The key findings were that most students saw the cation as more stable than the atom, and – of particular note – that most also saw the atom to be less stable than the anion. It is also of interest that at least half of the students in each group thought that the anion was as stable as the cation (Table 3). In view of this it was considered that the finding from the ionisation energy probe did reflect student thinking, rather than being an artifact of the way the item was read.

Table 3: Summary of main findings from original administration of the probe (Taber, 2000)

Among the group having studied some college chemistry, 13 of the 16 students used octet thinking (see above) to justify their judgements, e.g. "A [Na^+] is more stable than B [Na] as it has a complete octet". Some of the responses referred to both of the ions, Na^+ *and* Na^{7-}, having full outer shells (although the third electron shell can accommodate up to 18 electrons, i.e. $3s^2 3p^6 3d^{10}$),

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> A [Na^+] is more stable than B [Na] because its outer shell electron has eight electrons and is full where as B [Na] only has one electron in its outer shell and is therefore less stable. B [Na] is less stable than C [Na^{7-}] because again the outer shell of C [Na^{7-}] is full with eight electrons but B [Na] only has 1 electron in its outer shell and is less stable. C [Na^{7-}] and A [Na^+] are equally stable because both outer shells are full and the valency requirements have been fulfilled. Therefore both are equally stable.

11 of the 13 students in the group of students just commencing A level studies used octet thinking to support their judgements of relative stability, including this unequivocal example,

> If an atom has been filled up or all ready [already] full up of (8 outer electrons) it becomes stable and therefore it is unreactive. The atom will stay that way forever and not react or loose or gain any electrons.

Purposes of the present research

The findings from the Chemical Stability Probe initiated a series of further small-scale studies to confirm and extend the apparent finding that students imbued species with octet structures with inherent stability *even when such a species would be highly unstable in normal chemical environments*. Studies 1-3 sought to test out the original findings through three research questions.

Testing generalisation across student samples

Research Question 1: Would the judgements of relative chemical stability found in the original sample be replicated if the probe was used elsewhere?

Much of the research that led to the original derivation of the probe had taken place in one institution, and the probe had then been administered in the same college. Although there is no *a priori* reason to assume these students were particular in their understanding of chemical stability, and although statistical generalisability (which would require large random, or carefully composed representative, sampling) was not within the scope of the present research, it was clearly advisable to see if comparable findings are obtained in other institutional contexts.

Checking the significance of 'stability' judgements

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Research Question 2: Do students' judgements of the relative stability of the Na^+ actually imply that they think that it would be spontaneously generated from a sodium atom, and once formed would not recombine with an electron?

It is well known that learners often have different meanings for technical words met in science (e.g. Watts & Gilbert, 1983). Although the Chemical Stability Probe asks for judgements of relative stability, it does not check whether 'stability' has a similar meaning for respondents as it might for the chemist or chemistry teacher, so a complementary probe was prepared to test this.

Testing generalisation across chemical examples

Research Question 3: Do the judgements students make about the relative stability of Na^+ / Na / Na^{7-} reflect general principles that would be applied in other cases?

The original Chemical Stability Probe uses a single example, which could be seen as somehow a special case by students. Several variants of the probe were developed based around a bivalent metal, beryllium; a non-metal that does not readily form ions, carbon; a non-metal where the common ion does not have a full outer shell, chlorine; and the ground state and two excited states of the chlorine atom.

Methodology

The present research used pencil-and-paper instruments to survey student conceptions among groups of students. The individual instruments are detailed in relation to the distinct studies discussed below. Each instrument was printed upon one side of A4 and included diagrams (Figures 2-6), closed response items, and open-ended questions, asking students to make and justify judgements about relative stability and related processes.

Principles of instrument design and analysis

This is an example of 'confirmatory' research (Biddle & Anderson, 1986), where it is appropriate to provide fixed response categories deriving form earlier stages of research, to allow ready quantification of responses (Taber, 2007).

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A free response option was used to invite students to report their reasoning in their own words. This offered a check on whether students in different institutions would be thinking along similar lines to those responding in the earlier research. In the results below, the number of responses considered to be based upon octet thinking will be reported, i.e. where:

- the stability of a species is explained in terms of it having a full outer shell of electrons (or some term taken as synonymous); or
- lack of stability is explained in terms of a species not having a full outer shell of electrons (or some term taken as synonymous).

Some student responses are quoted below as exemplars of the main type of explanations offered (cf. Pope & Deniocolo, 1986).

The combination of closed- and open-ended items offers some degree of check on the trustworthiness of the instruments, as student reports of their rationale for judgements should appear consistent with the judgements indicated. High levels of discrepancy would indicate a problem: with item validity; reliability (if in the process of giving reasons the basis of students' original judgements changed); and/or the researcher's interpretation of the intended meanings of open responses. In the present research the vast majority of open responses offered reasoning that was considered to be clearly consistent with the students' judgements of stability.

The sequence of atomic models often presented in school and college science is known to be problematic (Justi & Gilbert, 2000; Taber, 2003b) and the choice of diagrams based on a simplified 'planetary' model of the atom could be seen to encourage thinking in terms of electron shells. This type of diagram reflects the target curriculum knowledge students are expected to learn by age 16, at the end of compulsory schooling, in the English system (DfEE/QCA, 1999). This is therefore the common starting point for developing more sophisticated understanding of atomic models (something students often find problematic, Taber, 2005) during the A level course itself. The representations used were of the type that would have been

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meaningful and most familiar to all those responding to the probes.

Sampling of learners

The data presented and discussed here were collected in the period leading up to, and during, a 'Teacher Fellowship' awarded by the UK's Royal Society of Chemistry (2000-2001). The theme of the project was 'challenging chemical misconceptions', and it was announced in *Education In Chemistry* (2000), a periodical widely available in UK schools and colleges. The author invited colleagues to administer, and comment upon, various diagnostic probes and classroom exercises that were being developed for the Royal Society of Chemistry to make publicly available to teachers.

The studies discussed here are based upon analysis of student responses from institutions that volunteered to help with the project. Teachers indicated their willingness to administer particular probes (where they taught classes for whom the probe was considered relevant). In all cases, teachers were sent sufficient copes of printed materials for their classes, and given instructions on how to administer the probes. Completed materials were posted back to the author for analysis, and teachers were asked for any comments on the instrument itself, or on issues of its administration, or arising from debriefing classes. This offered an opportunity to check face validity, and construct validity. There were no major issues arising from teacher feedback that necessitated changes in the design of the particular instruments discussed here. The final versions (reset in Royal Society of Chemistry house style, but otherwise as used in the research) are available in print (Taber, 2002b), and on line (RSC, undated).

By the nature of the (self-selecting) sample of institutions, the present work cannot be considered to provide *representative* results, so descriptive statistics are used to report the frequencies of different responses.

Study 1: Replication in a new institutional context

The opportunity was taken to refine the format of the probe to ask respondents to explain their reasoning *for each* of the comparisons. It was also decided to produce a version of the probe that reversed the order of the comparisons. For the administration

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of the probe the two versions of the questions were interleaved alternatively, so that distributing the sheets around a teaching group would give a rough randomisation of the two versions. The diagram given was also slightly amended (see Figure 3). This revised version of the probe was administered to a teaching group comprised of 19 students studying college level chemistry (i.e. A level) at an English Further Education College that had not previously been involved in the research.

Table 4: Judgements of stability in Study 1

In comparing the cation and atom, it made little difference which way round the question was worded - with 8/9 (original wording) and 9/10 (revised wording) students responding that the cation was more stable (Table 4). Similarly in the second comparison 7/9 and 10/10 felt that the anion was more stable than the atom. (In the final comparison there was more of a distinction, with 4/9 and 9/10 responding that the two ions were equally stable.)

Table 5: Judgements of relative stability from a second institution

The explanations given for why the cation was more stable than the atom reflected octet thinking, e.g. "[Na^+] has a full outer shell, and therefore has noble gas configuration making it more stable than [Na]". Responses to the 'reversed' version of the probe led to similar arguments,

> [Na] is less stable than [Na^+] because it has one electron in its outer energy level this means that electron is easily lost making it less stable. [Na^+] has its outer energy level full this means it is stable as it has noble gas configuration.

The view that the anion would also be more stable than the atom was also justified by octet thinking:

> Na^{7-} has a noble gas configuration also (isoelectronic with Ar), therefore stable compared to Na, with 1 outer electron.
>
> [Na^{7-}] is more stable than [Na] because [Na] only has one electron in its outer shell, but [Na^{7-}] has 8 making it stable."
>
> [Na^{7-} is more stable than Na because Na^{7-}] has full outer shell.

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An analysis of the reasons given showed that 55 of the 76 classified points reflected octet thinking. All but one of the 34 judgements (Table 4) that the ions were more stable than the neutral atom were supported by references to the stability of specific electronic configurations or the number of electrons. The only explanation that did not make explicit references of this type could certainly be construed as consistent with this form of thinking,

> [Na is less stable than Na^+ because] It has one electron on the outer shell and it will want to loose it.

Study 1 shows that among these students in a second institution, the respondents were drawing upon octet thinking when judging which species they would *label* stable. It remained possible that students may have very different notions of what 'stable' implies. In particular, the validity of asking students to make decontextualised judgments of this kind might be questioned (an issue considered in the discussion section of the paper).

Study 2: The significance of relative stability

It was clear that many students at college level judged not only Na^+ but also the chemically unlikely Na^{7-} species as 'stable' (Tables 3 & 5). However, it could not be assumed that the students making these judgements generally associated 'stability' with not undergoing changes. Study 2 explored whether the term 'stable' was just being used as a label that they had acquired, or whether they saw chemical stability as a property with real consequences.

Figure 2: Diagram used in Study 2

The Stability/Reactivity probe (Taber, 2002a: 105-106) concerned the species Na^+ and $Na^{\bullet}$ (see Figure 2). It had three components, the first of which asked respondents to judge which species was more stable (cf. Study 1). The second question was designed to find out whether students who judged a sodium cation to be more stable would also think that the atom should spontaneously emit an electron (the options were: The sodium atom will emit an electron to become an ion; The sodium ion and electron will combine to become an atom; Neither of the changes suggested above will occur; I do not know which statement is correct). The third part of the probe

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asked the respondents which of the two species (Na^+ or Na) they thought were *most reactive*. Each section asked respondents to explain their choice.

Results from the Stability/Reactivity Probe

The probe was administered to three A level teaching groups in institutions in England not involved in the previous studies - two school sixth forms, and a further education college. As the individual sample sizes are small (group sizes of 11, 6 and 11 respectively) the results have been pooled (see Table 6).

Table 6: Results from Study 2 (pooled data)

It was found that most of the students considered the sodium ion to be more stable than the sodium atom (Table 6), and so in this respect the respondents had similar views to the students in Study 1.

In Question 2, a majority of the respondents selected the option that a sodium atom would emit an electron, about three times as many as thought that an ion would combine with an electron to form an atom (Table 6). This suggests that most of the students judging the ion to be more stable *do* interpret this in a similar sense to its formal meaning, and are not just using 'stable' as a label for a certain types of structure.

Question 3 asked about the 'reactivity' of the atom and cation. This is considered to be a problematic question as there is a good case for reserving the terms 'reaction', 'reactive' and 'reactivity' to descriptions at the macroscopic scale and using different terms to describe sub-microscopic, molecular scale, processes (Taber, 2001a). However, this did not seem to be an issue with the students, most of who were able to give perfectly coherent explanations for their selected responses. Most of the sample considered the atom as the more 'reactive' species, although - interestingly - not quite as many as considered the ion the more stable.

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The stability of the ion was explained in terms of it having "a full outer shell of electrons" or because it "has 8 outer electrons", which gave a noble gas structure,

> The sodium ion has a full outer shell → 8 electrons. E.g. the noble gases have a full outer shell → not reactive.

23 of 24 judgements that the ion was more stable; 13/18 of judgements that the atom would emit an electron; and 11 of the 18 judgements that the ion was more reactive, were justified by octet thinking.

One respondent conceptualised the question in a chemical context (a point returned to in the Discussion, below),

> I'm not sure if 'emit' is the right word, but it will donate it to an electron receiver, such as an element in period 7 of the periodic table.

It was common, however, for the students' justifications to focus on the specific $Na \rightarrow Na^{+} + e^{-}$ process,

> When the sodium atom emits an electron it will have a full outer shell as an ion. This is more stable. It is less likely that the sodium ion would gain an electron as this would make it less stable.

Study 3: Range of application of students' chemical stability concept

As limiting the research to consideration of sodium species could not exclude the possibility that judgements elicited might reflect some particular feature of students' perceptions of this example (e.g. the influence of ubiquitous textbook diagrams of a sodium atom 'donating' an electron to a chlorine atom), four variants of the chemical stability probe were prepared (see Figures 4-7). ThIn the CS(Beryllium)P the example of beryllium was used (see Figure 4), with - parallel to the sodium case - a highly unstable anion (Be^{6-}) and a relatively stable cation (Be^{2+}) which, none-the-less, would not form spontaneously from the atom. The main difference between this and the original probe (besides the actual charge values on the ion) was that the stable cation did not have an octet of electrons (as beryllium is in period 2 of the periodic table, whereas sodium is in period 3).

In the CS(Carbon)P the comparison concerned the carbon atom, and the two carbon ions with FOS, C^{4+} and C^{4-} (see Figure 5). From a scientific viewpoint *both* of these

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ions are highly unstable. This made an interesting comparison with the sodium case where suggestions that Na^+ was more stable than the atom could *potentially* be justified by the argument that it must be - as it was a commonly found species, unlike the atom (see the discussion, below).

The other two new versions of the probe were intended to explore other features of students' notions of chemical stability. The original research had found that students appeared to assume species with *octet* structures were stable, although in their explanations they commonly referred to FOS. These descriptors are only technically equivalent for the second (L, n=2) electron shell. In the original version of the probe the sodium anion presented (Na^{7-}) had an octet structure, but not (despite student comments to the contrary) a FOS. The CS(Anions)Probe presented a chlorine atom, the common anion Cl^- (which has an octet of outer shell electrons, but not a FOS) and the highly 'unlikely' species Cl^{11-} that with 18 outer shell electrons would literally have a FOS. (This question also differed from the other comparisons so far discussed in that the Cl^- ion *would* spontaneously form, and so could genuinely be considered more stable than the neutral atom.)

The final variant of the probe also concerned chlorine, but - unlike the other probes - only included neutral atoms. The three species presented in the CS(Atoms)P were the ground state atom, and two version of an excited state where an electron has been promoted to the outer (M, n=3) shell from either the first (K, n=1) or second (L, n=2) shell. In this comparison the two excited atoms both had octets of electrons in their *outer* shells, but were energetically unstable compared with the ground state.

Although it is possible to consider other comparisons, it was felt that the five versions of the chemical stability probe could collectively elicit various aspects of student thinking about chemical stabilityThe expanded set of probes (Taber, 2002a: 103-104) was administered in five further institutions (three school sixth forms, a sixth form college and a further education colleges) to groups of students studying A level chemistry. The total sample size was 152 students (with samples from within each institution varying in size from 18 to 58). As the five different probes in the set were provided already sequenced, teachers were asked to simply distribute probes around the class from the deck of probes. This meant that each student would be answering

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different questions from others around them, and that approximately equal numbers of each probe would be completed. The overall results of Study 3 are presented in Table 7, and explained below.

Table 7: Responses to 5 versions of the Chemical Stability Probe

Responses to the Variegated Chemical Stability Probe

Figure 3: Species presented in Studies 1 and 3

33 students in the five institutions responded to the original version of the probe, making comparisons between the three species Na^{+}/Na/Na^{7-} (see Figure 3). Although only a few of the students in this Study (cf. Studies 1 and 2) thought the anion would be as stable as the cation, respondents generally thought that both of the ions would be more stable than the atom (Table 8).

Table 8: Key findings comparing species Na^{+}, Na, Na^{7-}

The majority of the explanations for why the ions were more stable than the atom were based on octet thinking (see Table 8).

Figure 4: Species presented Study 3

In the first variant the example of beryllium was used (see Figure 4), with - parallel to the sodium case - a highly unstable anion (Be^{6-}) and a relatively stable cation (Be^{2+}), which, none-the-less, would not form spontaneously from the atom. A key difference between this and the original probe was that the stable cation did not have an octet of electrons (as beryllium is in period 2 of the periodic table, whereas sodium is in period 3).

27 students in the five institutions responded to this version of the probe (see Table 7). They mostly recognised that the beryllium anion would be less stable than the cation. However almost half thought that the anion would be more stable than the atom (Table 9).

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Table 9: Key findings comparing species Be^{2+}, Be, Be^{6-}

Even though the beryllium cation did not have an octet, it was still seen as more stable than the atom "as the electron shells are full and thus stable". The beryllium atom was considered to 'want' to obtain such a state: "Outer shell is full in [Be^{2+}]. So it is more stable than [Be], which wants to loose two electrons." Among those students who thought that the atom was less stable than the anion, there were familiar references to how Be^{6-} "has a complete outer shell so is stable, whereas [Be] has not got a full outer shell" (see Table 9).

Figure 5: Species presented in Study 3

In the second variant probe, the comparison concerned the carbon atom, and the carbanion and carbocation that would have full outer shells, C^{4+} and C^{4-} (see Figure 5). In normal chemical contexts, *both* of these ions are highly unstable. Students at this level would be expected to know that carbon compounds are usually primarily covalent, rather than ionic.

Thirty students in the five institutions responded to this variant of the probe. It was found that in the case of both of the ions a small *majority* among the respondents believed that the ion would be more stable than the atom (Table 10).

Table 10: Key findings comparing species C^{4+}, C, C^{4-}

Student explanations for judging the highly charged ions as more stable than the atom were again commonly based on octet thinking (Table 10).

Figure 6: Species presented in Study 3

In the original version of the probe the sodium anion presented (Na^{7-}) had an octet structure, but not (despite student comments to the contrary) a full outer shell. The third variant of the probe presented a chlorine atom, the common anion Cl^{-} (which because of the electron affinity of chlorine, would spontaneously form if a 'free' electron is available, and so might reasonably be considered more stable than the neutral atom) and the species Cl^{11-} that with 18 outer shell electrons would literally

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have a full outer shell (Figure 6).

31 students in the five institutions responded to this variant. Most of the students recognised that the Cl^- anion would be more stable than the atom (Table 7), and most recognised that this common anion would be more stable than the unlikely Cl^{11-}. About half of the sample thought that this highly charged species would be less stable than the neutral atom. However, as summarised in Table 11, there was still a considerable level of support for the notion that Cl^{11-} would be a stable species.

Table 11: Key findings comparing species Cl, Cl^-, Cl^{11-}

Student judgments were commonly supported by octet thinking (see Table 11). The reasons that students gave for considering that Cl^- was more stable than the chlorine atom were again often variations on the theme that Cl^- "has a full outer shell". One of the respondents who thought that the chlorine atom was *more* stable than the Cl^{11-} anion implied this was because it was *closer to* an octet structure, i.e. that Cl "only has to gain 1 electron [whereas Cl^{11-}] loses 10". Where students judged the Cl^{11-} ion as being *more* stable than the atom, they tended to provide similar reasons, in terms of Cl^{11-} having "a full outer shell of electrons making it more stable". Some of the students who believed that the two anions were equally stable justified this in terms of *both* species (despite both being chloride ions having different numbers of electrons in their valence shell) having full outer shells: "Both have fully outer shells and so do not want to loose or gain e^- and are both equally stable".

The Cl^{11-} species was an unfamiliar and highly charged ion, compared with the common Cl^- anion that is familiar in school science. The unlikely Cl^{11-} species was chosen for the probe because it *would* have a full outer shell of electrons, but was judged by some students to have "too many electrons in its outer shell", or "more electrons than it should", whereas it was claimed that Cl^- was more stable than Cl^{11-} because Cl^- "has a full outer shell".

Figure 7: Species presented in Study 3

The final variant of the probe also concerned chlorine, but - unlike the other probes - only included neutral atoms. The three species presented were the ground state atom,

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and two version of an excited state where an electron has been promoted to the outer (M, n=3) shell from either the first (K, n=1) or second (L, n=2) shell. In this comparison the two excited atoms both had octets of electrons in their *outer* shells, but were energetically unstable compared with the ground state (see Figure 7).

Deleted: 12

Table 1: Key findings comparing states of the chlorine atom

31 students in the five institutions responded to the final version of the probe. Most of the respondents thought that the highly excited state was either more stable than, or equally as stable as, the less excited state (see Table 12). Equal numbers of respondents believed that the 2.7.8 configuration was more stable than the ground state as thought that the converse should be true. Most of the respondents thought that the least stable species (1.8.8) would be *more stable* than the ground state.

The two excited states were considered to be *equally stable* by some students because "they both have full outer shells". This type of response did not generally seem to mean students had failed to realise that *the other* shells were not full, as there references to the unfilled shells, "Both have one shell that is unfilled and requires only one electron to complete it. They have filled outer shells". One respondent argued that F [ground state] is less stable than D [highly excited] because "D has a full outer shell and is ∴ relatively stable despite only 1 e^- in the inner shell compared with only 7 e^- in F's outer shell" and another argued the ground state was less stable because the "Electron 'gap' is on outermost shell therefore more easily reacts". It seems that these students were not ignoring the inner shells, but thought that the outer shell was more significant: "E has a full outer shell of electrons unlike F. Electrons are lost from the outermost shells".

Discussion

The main findings from this series of studies can be summarised as follows:

- Respondents commonly judged stability in terms of the electronic structure of species, without paying heed to other factors (such as net charge);
- Species judged as stable were those considered to have full outer electron

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shells, which for most respondents was equated with 8 electrons in the case of the third shell;

- The notion of stability was not purely nominal, but was found to imply that a species would form spontaneously, and would then not readily change.

These findings are in line with previous research where it was found that the 'desirability' of full electron shells was used as the key explanatory principle underpinning a common alternative conceptual framework (Taber, 1998).

The research presented here, like all research, has limitations. Convenience sampling has been used, although consistency of the main findings across a range of institutions suggests a general tendency among learners in comparable contexts. Space considerations restrict presentation of the reasons given by the students for their choices to a limited number of exemplar responses that give a flavour of *the most common type of argument* of full outer electron shells having an inherent stability.

Judging stability in context

What the present paper shows is that when student responses are considered against target knowledge:

a) students' use of 'stable' does not match the contextual limitations that their teachers are likely to intend;
b) students' application of an octet criterion for stability extends far beyond its range of application.

It is important to acknowledge the decontextualised nature of the tasks. As indicated at the outset of the paper, judgements of chemical stability can only be meaningfully made in contexts. Xenon is a stable element – but under appropriate conditions it will react. Phosphorus and sodium are reactive elements, but relatively stable when stored under water or oil respectively. 'Respectively' is needed, or else we will demonstrate just how reactive sodium can be! Neither a sodium atom nor a sodium ion can be meaningfully judged 'stable' or 'unstable' without knowledge of the conditions being

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considered. This raises the issue of the validity of asking students to make such judgements, and the potential of such probes for encouraging students to think of stability in absolute terms.

It was clear from the studies that, although asking students to make decontextualised comparisons of stability does not reflect good science, it was a task that students found meaningful and readily undertook. That is, it seemed to tap into their existing thinking. Unlike some research instruments that look to 'force' a choice, a 'do not know' option was always available on these probes, but (as Tables 1, 2, 4, and 7 show) few students felt the need to use this option, nor to comment in the free-response sections on the task being ambiguous or meaningless. Study 2 suggests that students' decontextualised choices in Studies 1 and 3 reflect judgments of whether species would spontaneously emit or attract free electrons.

Table 13: Consistency of judgements across samples

It should be noted here that students commonly judged as stable chemical species that would *not* be stable in any familiar or chemically feasible environment. If judging Na^{+} more stable than Na, and so liable to be spontaneously produced, can be seen as a problem of ignoring context, then judging Na^{7-} as stable (as most of the students do – see Table 13) cannot be explained so readily. The Na/Na^{7-} comparison shows that these students generally see the octet criterion of stability as overriding factors such as which species are known to be found 'in nature'; the chemical nature of metals (forming cations); or the inherent instability of highly charged species. Study 3 shows this is not an isolated 'special' case, as substantial proportions (nearly two-fifths to over half) of those surveyed see Be^{6-}, C^{4-}, C^{4+}, and even Cl^{11-} – which did not even fit

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many students' notion of a full third electron shell - as more stable than the atoms. The perceived stability of excited (by definition, less stable) atoms with full outer shells in Study 3 provides an even less equivocal comparison: the excited states are less stable, can only be produced by 'exciting' the ground state, and will spontaneously 'relax' back to the ground state. For many students it seems that judging chemical stability means applying the 'octet rule' heuristic as if an absolute rule: one to which they admit no exceptions.

Alternative conceptions

It is well established that learners develop many alternative conceptions in chemistry (Duit, 1991; Driver, Squires, Rushworth & Wood-Robinson, 1994; Taber, 2002a; Kind, 2004), and that some of these cannot be explained in terms of intuitive understandings based on out-of-class experience of the phenomena (e.g. Osborne, 1985; Taber, in press), or folk-science versions of the topics (Solomon, 1993) – and seem to derive in part from the way the subject is taught (Taber, 2005).

It could be suggested that given the tendency of students to develop alternative conceptions in this area, it is inappropriate, or even irresponsible, to present students with tasks of the type used in this research that could actually suggest or reinforce alternative conceptions. However, the present research was part of a sequence of studies designed to follow-up open-ended interviews where students spontaneously demonstrated these ways of thinking (Taber, 1998, 2000), and the development of diagnostic instruments can support teachers in making explicit and challenging these ideas (Driver & Oldham, 1986; Taber, 2001a). The probes were published in a volume of classroom resources that included teacher support notes (Taber, 2002b),

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and accompanied by a text explaining the nature and significance of the alternative conceptions (Taber, 2002a).

Implications for teaching

Some of the reasons why learning about the basic concepts (substance, reaction, etc.) and models (especially particle models) of chemistry can be so difficult were considered in the introduction. Students have also been found to have limited appreciation of the nature of models used in science (Grosslight, Unger, Jay & Smith, 1991) and may readily become confused by the progression of models used in teaching chemistry (Carr, 1984; Taber, 2005), which may themselves sometimes lack rigour (Justi & Gilbert, 2000).

It was suggested earlier that there is something of an explanatory vacuum at secondary level where notions of reactivity and stability may have little underpinning. This is linked to well-recognised difficulties of curriculum sequencing (Johnstone, 2000; Taber, 2001a; Johnson, 2002; Nelson, 2002). Upper secondary teachers are expected to find ways to teach a complex and abstract subject, largely based on making the hypothetical but counter-intuitive 'quanticles' (Taber, 2005) of particle models real for students (Ogborn, Kress, Martins & McGillicuddy, 1996), but *without* introducing many of the conceptual tools necessary to offer convincing versions of the explanatory stories (cf. Millar & Osborne, 1998) of science.

It seems likely then that a pedagogic learning impediment is at work here – where the way in which the subject is taught has unintended and undesirable consequences for learning (Taber, 2005). Students acquire a simple heuristic (full outer shell = stable) that 'fills the explanatory vacuum'.

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The present research shows the importance of teachers always making explicit assumptions about context when using relative terms like 'stable'. Teachers should for example avoid *exclusive* focus on the outer shell, as this may inadvertently be contributing to about half the students sampled here thinking that a full outer shell will give stability even when it is achieved by promoting electrons from inner shells.

Sodium, the material, is - under common conditions - reactive, and sodium ions, in a chemical context such as a sodium chloride lattice, are relatively stable. The chemistry teacher needs to be explicit that it is in such contexts that we can say that the sodium cation is more stable than the atom. As far as many college students are concerned Na^+ *is* more stable than Na: they therefore transfer this judgement from a chemical context, into what might be labelled a physical context (Taber, 2003a) and – as seen in Study 2 – may therefore expect sodium atoms to spontaneously eject electrons.

This suggestion fits well with recommendations from previous work (Taber, 1998, 2001a, 2003b) that teachers focus more on the physical forces at work during chemical processes. The overall charge on species; the electrical environments in which species may be considered stable; and the electrical interactions needed for electrons to be 'lost' or 'gained' provide the context for thinking about when and why a species may be considered stable.

The next swing of the methodological pendulum

Educational research is often characterised as being of two main types (Eybe & Schmidt, 2001) commonly presented as being opposed, e.g. positivist vs. interpretivist (e.g. Taber, 2007). However within a research programme (Lakatos, 1970), a wide range of methods may be employed (NRC, 2002), according to the purposes of particular studies. The present research is undertaken within a well established

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research programme that explores aspects of learning in science (Taber, 2006), where it has long been accepted that detailed studies of specific learners and teaching/learning contexts can inform, and be informed by, research that looks to identify *common* features of learning in science. (e.g. Driver & Easley, 1978; Treagust, 1988).

The research programme moves forward by the iterative process of studies of individual learners *informing*, and *being informed by* surveys of populations and studies of teaching and learning in classrooms (Taber, 2007). So findings from in-depth interviews raised issues (Taber, 1998, 2000) that have been explored here by survey techniques that suggest that those findings reflect widespread ways of thinking. The studies reported here raise further issues that may best be studied through a further stage of in-depth work.

Previous research suggests that the explanations college students offer for chemical phenomena vary considerably in terms of complexity and of match to both scientific values (e.g. coherence, being causal etc) and to the models presented in the curriculum (Taber & Watts, 2000). However, the apparent readiness with which octet thinking is adopted by so many students, hints at this idea 'resonating' strongly with many students' intuitions (Taber, in press). The decontextualised nature of the tasks reported here is a major limitation to the research, and further work is indicated to explore student thinking when asked about the stability of chemical species in various chemical environments. We might expect that at college level students should be capable of moving beyond such absolutist thinking as equating full electron shells with stability (Perry, 1970), but other studies suggest that students at this level may often focus on only one of several relevant factors when making judgements about the

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submicroscopic world (Taber & Tan, 2007), reflecting the limited forms of reasoning found to be common in learning science at secondary levels (Driver, Leach, Millar & Scott, 1996).

The complexity of student learning suggests the need for in-depth longitudinal case studies that can begin to model learners' evolving conceptual ecologies and improve our understanding of how and why such conceptions are acquired, and to what extent, and under what conditions, students will progress towards more scientific understandings (Taber, 2001b).

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Figures

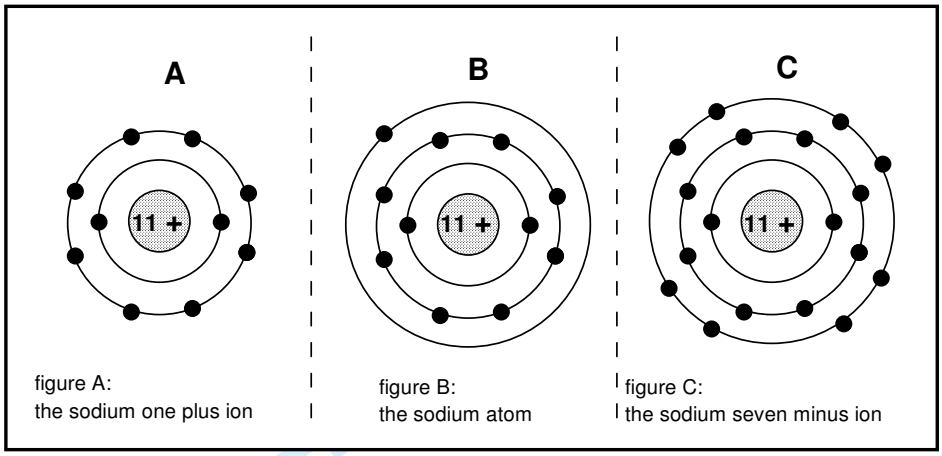

Figure 1: Diagram presented in the original probe (Taber, 2000)

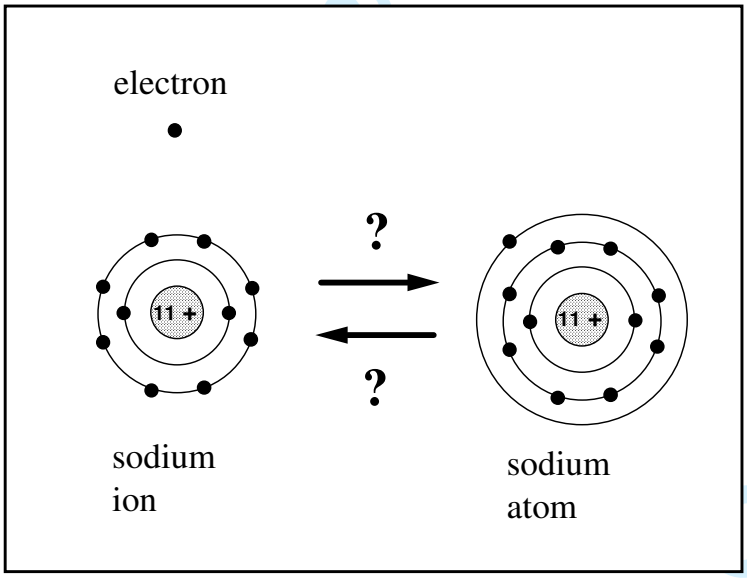

Figure 2: Diagram presented in Study 2

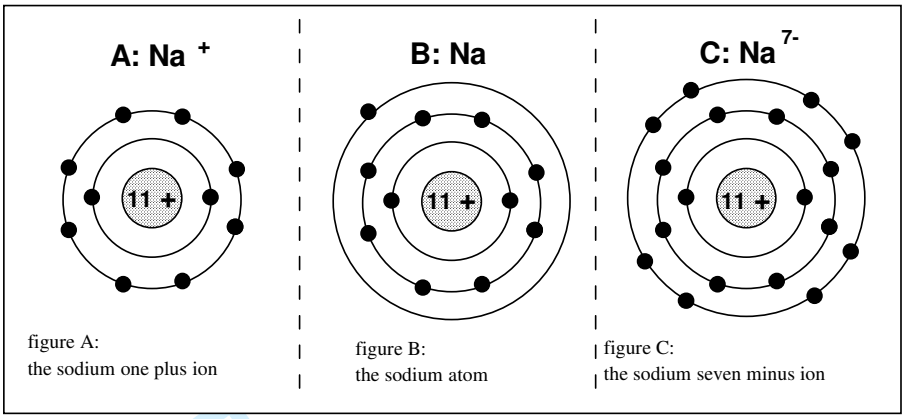

Figure 3: Species presented in Studies 1 and 3

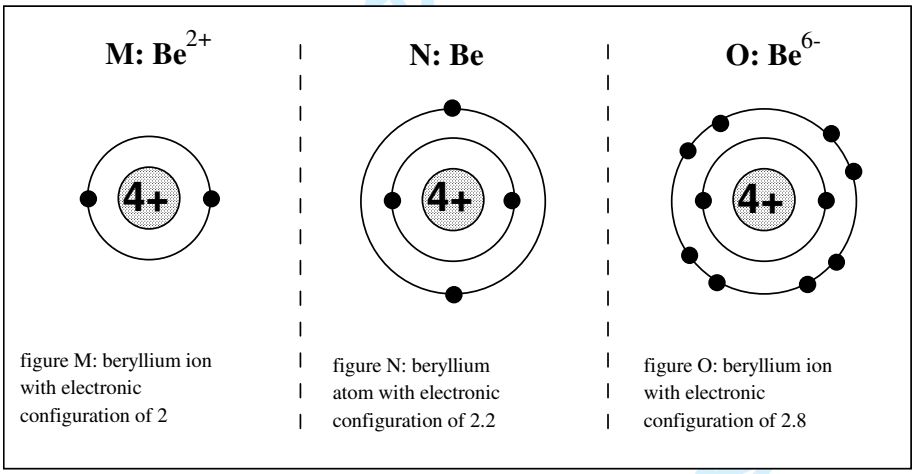

Figure 4: Species presented in Study 3

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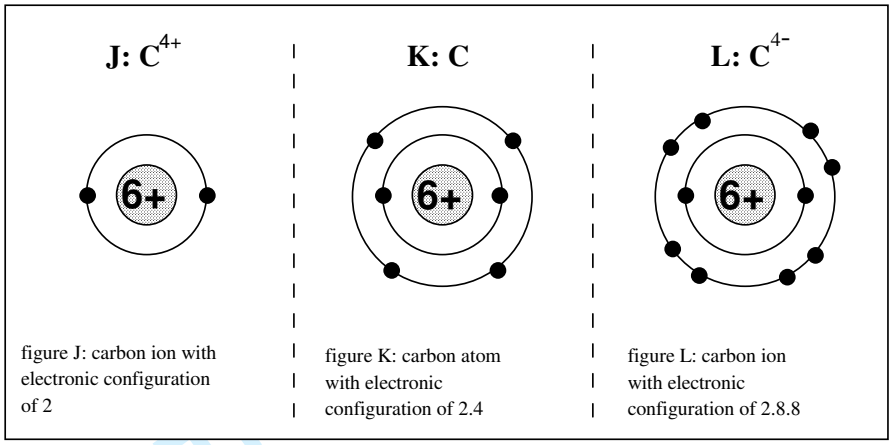

Figure 5: Species presented in Study 3

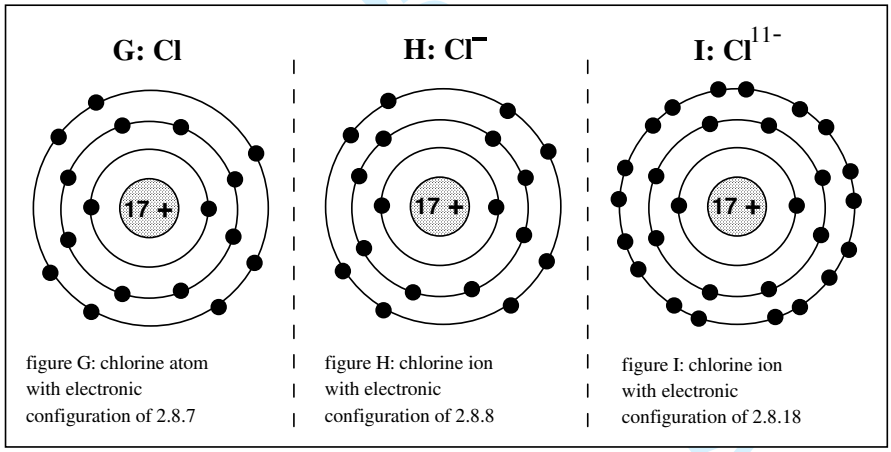

Figure 6: Species presented in Study 3

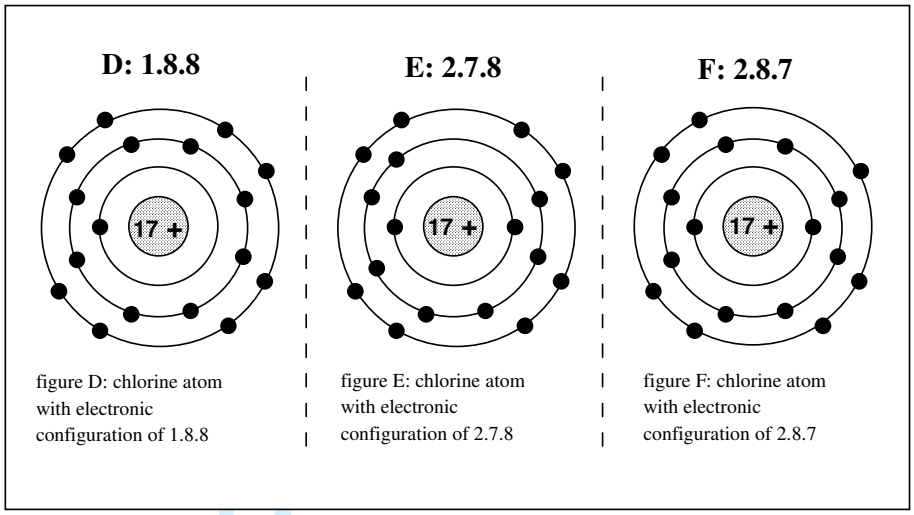

Figure 7: Species presented in Study 3

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Tables

Q1	**Na^+>Na**	**13**	Na^+=Na	2	Na^+<Na	0	Na^+?Na	1	*	16
Q2	Na>Na^{7-}	6	Na=Na^{7-}	0	**Na<Na^{7-}**	**10**	Na?Na^7	0	*	16
Q3	Na^{7-}>Na^+	0	Na^{7-}=Na^+	8	Na^{7-}<Na^+	8	Na^{7-}?Na^+	0	*	16

Table 1: Judgements of stability from an A level group having studied relevant topics

Note on tables: The following symbols are used: > is more stable than; = are equally stable; < is less stable than; ?: do not know: respondents could not judge which species is more stable; •: subtotal of respondents; * total number of respondents.

Q1	**Na^+>Na**	**11**	Na^+=Na	0	Na^+<Na	2	Na^+?Na	0	*	13
Q2	Na>Na^{7-}	2	Na=Na^{7-}	0	**Na<Na^{7-}**	**11**	Na?Na^7	0	*	13
Q3	Na^{7-}>Na^+	1	Na^{7-}=Na^+	9	Na^{7-}<Na^+	3	Na^{7-}?Na^+	0	*	13

Table 2: Judgements of stability from a group of students commencing A level studies

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response selected	experienced college group	students entering college
Na^+ is more stable than Na	13/16	11/13
Na is less stable than Na^{7-}	10/16	11/13
Na^+ and Na^{7-} are equally stable	8/16	9/13

Table 3: Summary of main findings from original administration of the probe (Taber, 2000)

Q1	**Na^+>Na**	**8**	Na^+=Na	0	Na^+<Na	1	Na^+?Na	0	•	9
Qi	**Na<Na^+**	**9**	Na=Na^+	0	Na>Na^+	1	Na?Na^+	0	•	10
	•	**17**	•	0	•	2	•	0	*	19
Q2	Na>Na^{7-}	1	Na=Na^{7-}	1	**Na<Na^{7-}**	**7**	Na?Na^{7-}	0	•	9
Qii	Na^{7-}<Na	0	Na^{7-}=Na	0	**Na^{7-}>Na**	**10**	Na^{7-}?Na	0	•	10
	•	1	•	1	•	**17**	•	0	*	19
Q3	Na^{7-}>Na^+	0	**Na^{7-}=Na^+**	**4**	Na^{7-}<Na^+	5	Na^{7-}?Na^+	0	•	9
Qiii	Na^+<Na^{7-}	0	**Na^+=Na^{7-}**	**9**	Na^+>Na^{7-}	1	Na^+?Na^{7-}	0	•	10
	•	0	•	**13**	•	6	•	0	*	19

Table 4: Judgements of stability in Study 1

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judgement	respondents
Na^{+} is more stable than Na	17/19
Na^{7-} is more stable than Na	17/19
Na^{7-} is as stable as Na^{+}	13/19

Table 5: Judgements of relative stability from a second institution

Q	Response selected	responses
1	The sodium atom is more stable than the sodium ion	3
	The sodium ion is more stable than the sodium atom	**24**
	The sodium ion and sodium atom are equally stable	0
	I do not know which statement is correct	1
	N=	28
2	**The sodium atom will emit an electron to become an ion**	**18**
	The sodium atom and electron will combine to become an atom	5
	Neither of the changes suggested above will occur	3
	I do not know which statement is correct	2
	N=	28
3	The sodium atom is more reactive than the sodium ion	18
	The sodium ion is more reactive than the sodium atom	10
	The sodium ion and sodium atom are equally reactive	0
	I do not know which statement is correct	0
	N=	28

Table 6: Results from Study 2 (pooled data)

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Q1	**Na^{+}>Na**	**27**	Na^{+}=Na	1	Na^{+}<Na	3	Na^{+}?Na	2	*	33
Q2	Na>Na^{7-}	11	Na=Na^{7-}	1	**Na<Na^{7-}**	**21**	Na?Na^{7-}	0	*	33
Q3	Na^{7-}>Na^{+}	2	Na^{7-}=Na^{+}	4	Na^{7-}<Na^{+}	27	Na^{7-}?Na^{+}	0	*	33
Q4	1.8.8>2.7.8	10	1.8.8=2.7.8	10	1.8.8<2.7.8	7	1.8.8? 2.7.8	4	*	31
Q5	**2.7.8>2.8.7**	**14**	2.7.8=2.8.7	1	2.7.8<2.8.7	14	2.7.8? 2.8.7	2	*	31
Q6	2.8.7>1.8.8	10	2.8.7=1.8.8	1	**2.8.7<1.8.8**	**17**	2.8.7? 1.8.8	3	*	31
Q7	Cl>Cl^{-}	3	Cl=Cl^{-}	2	Cl<Cl^{-}	26	Cl? Cl^{-}	0	*	31
Q8	Cl^{-}>Cl^{11-}	19	Cl^{-}=Cl^{11-}	9	Cl^{-}<Cl^{11-}	2	Cl^{-}? Cl^{11-}	1	*	31
Q9	**Cl^{11-}>Cl**	**12**	Cl^{11-}=Cl	0	Cl^{11-}<Cl	15	Cl^{11-}? Cl	4	*	31
Q10	**C^{4+}>C**	**17**	C^{4+}=C	0	C^{4+}<C	12	C^{4+}? C	1	*	30
Q11	C>C^{4-}	13	C=C^{4-}	0	**C<C^{4-}**	**17**	C? C^{4-}	0	*	30
Q12	C^{4-}>C^{4+}	5	C^{4-}=C^{4+}	15	C^{4-}<C^{4+}	9	C^{4-}? C^{4+}	1	*	30
Q13	**Be^{2+}>Be**	**20**	Be^{2+}=Be	0	Be^{2+}<Be	7	Be^{2+}? Be	0	*	27
Q14	Be>Be^{6-}	11	Be=Be^{6-}	3	**Be<Be^{6-}**	**13**	Be? Be^{6-}	0	*	27
Q15	Be^{6-}>Be^{2+}	3	Be^{6-}=Be^{2+}	4	Be^{6-}<Be^{2+}	16	Be^{6-}? Be^{2+}	4	*	27

Table 7: Responses to 5 versions of the Chemical Stability Probe

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judgement of relative stability	selection of judgement	octet thinking justification
Na^{+} is more stable than Na	27/33	22/27
Na^{7-} is more stable than Na	21/33	17/21

Table 8: Key findings comparing species Na^{+}, Na, Na^{7-}

judgement of relative stability	selection of judgement	octet thinking justification
Be^{2+} is more stable than Be	20/27	13/20
Be is less stable than Be^{6-}	13/27	13/13

Table 9: Key findings comparing species Be^{2+}, Be, Be^{6-}

judgement of relative stability	selection of judgement	octet thinking justification
C^{4+} is more stable than C	17/30	16/17
C is less stable than C^{4-}	17/30	15/17

Table 10: Key findings comparing species C^{4+}, C, C^{4-}

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judgement of relative stability	selection of judgement	octet thinking justification
Cl^{11-} is at least as stable as Cl^{-}	11/31	8/11
Cl^{11-} is more stable than the atom	12/31	9/12

Table 11: Key findings comparing species Cl, Cl^{-}, Cl^{11-}

Judgement of relative stability	selection of judgement	octet thinking justification
Cl (1.8.8) is at least as stable as Cl (2.7.8)	20/31	14/20
Cl (2.7.8) is more stable than Cl (2.8.7)	14/31	11/14
Cl (2.8.7) is less stable than Cl (1.8.8)	17/31	12/17

Table 12: Key findings comparing states of the chlorine atom

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Proportion of students selecting...	Taber, 2000 study	Study 1	Study 2	Study 3
…Na^+ is more stable than Na	24/29	17/19	24/28	27/33
…Na is less stable than Na^{7-}	21/29	17/19	(not applicable)	21/33

Table 13: Consistency of judgements across samples

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