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AS and A LEVEL

Delivery Guide

CHEMISTRY B (SALTERS)

H033/H433
For first teaching in 2015

Formulae, equations and amount of substance

Version 2

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Introduction

AS and A LEVEL
CHEMISTRY B (SALTERS)

Delivery guides are designed to represent a body of knowledge about teaching a particular topic and contain:

- Content: A clear outline of the content covered by the delivery guide;
- Thinking Conceptually: Expert guidance on the key concepts involved, common difficulties students may have, approaches to teaching that can help students understand these concepts and how this topic links conceptually to other areas of the subject;
- Thinking Contextually: A range of suggested teaching activities using a variety of themes so that different activities can be selected which best suit particular classes, learning styles or teaching approaches.

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Curriculum content

Learners should be able to demonstrate and apply their knowledge and understanding of:

EL(a) atomic number, mass number, isotope, Avogadro constant (N_A), relative isotopic mass, relative atomic mass (A_r), relative formula mass and relative molecular mass (M_r)

EL(b) (i) the concept of amount of substance (moles) and its use to perform calculations involving: masses of substances, empirical and molecular formulae, percentage composition, percentage yields, water of crystallisation

(ii) the techniques and procedures used in experiments to measure masses of solids

EL(c) (i) the concept of amount of substance (moles) and its use to perform calculations involving concentration (including titration calculations and calculations for making and diluting standard solutions);

(ii) the techniques and procedures used in experiments to measure volumes of solutions; the techniques and procedures used in experiments to prepare a standard solution from a solid or more concentrated solution and in acid–base titrations

EL(d) balanced full and ionic chemical equations, including state symbols

EL(x) use of data from a mass spectrum to determine relative abundance of isotopes and calculate the relative atomic mass of an element

DF(a) the concept of amount of substance in performing calculations involving: volumes of gases (including the ideal gas equation $pV = nRT$), balanced chemical equations, enthalpy changes; the techniques and procedures used in experiments to measure volumes of gases

ES(a) the concept of amount of substance in performing calculations involving atom economy; the relationship between atom economy and the efficient use of atoms in a reaction

OZ(i) calculations, from given data, of values for composition by volume of a component in a gas mixture measured in percentage concentration and in parts per million (ppm)

DM(a) manganate(VII) titrations; non-structured calculations based on these and any other types of titration ***(A Level only)***

Approaches to teaching the content

Formulae and equations

Early ideas arrive in a hierarchical pedagogy after the initial reinforcement of atomic structure. In Elements of Life *(EL)* we are reminded of the idea that 'matter cannot be created or destroyed' in a chemical reaction (conservation of mass). This is used, along with the pre-requisite of *learning* the reactants and products of different reactions (i.e. word equations), to construct balanced symbol equations. To be successful in this, learners have to know and recognise simple formulae and understand that formulae represent a whole number ratio of types of atom or ion. The link between the basic idea of conservation of mass and conservation of particles (atom/ion) is key here.

Amount of substance

Learners start from the idea of relative masses – atomic, molecular and formula – and then have to make the cognitive leap to the idea that, if we are to measure 'how much' of a reactant or product we have (in terms of mass or volume) we need to have a very large number of our reactant and product 'particles'. To simplify calculations, a unit is used to express 'amount of substance' in more manageable numbers – this is the mole.

The Avogadro constant is in effect the proportionality constant that connects the quantities 'amount of substance' and 'number of particles'. It should be explained to learners that the Avogadro constant is no random number, but was experimentally determined as the number of atoms of a given element that equated to that element's atomic (isotopic) mass in grams. It follows that the numerical value of the mass of 1 mol of a compound (in grams) will be equal to the value of the relative molecular or formula mass.

Learners will need considerable practice in working out the mass of various amounts of substance in grams and vice versa, and there are many opportunities in *EL* to practice these calculations. As this storyline progresses, the concepts are applied to concentrations of solute in solutions. This can be connected to teaching of acid–base titrations; at this point it is recommended that learners are introduced to structured calculations, although they will be required to attempt less structured calculations as the course progresses. (Candidates taking the AS Level qualification will be expected to handle unstructured calculations in their examinations.) This area is then extended in *Developing fuels (DF)* to include gas volumes and the ideal gas equation.

In the second year of the course, for A Level candidates only, this area is revisited in the context of redox titrations in *Developing metals (DM)*. This provides an excellent point to check learners remember the concepts from the previous year. At this point, fully non-structured calculations should be introduced if they have not already.

Abundances

There are several topics in the course that are related to the concept of abundance. The concepts behind these topics are generally not complex, but the calculations – often related to percentages – can be tricky for some learners. Working on the skills involved in these calculations is valuable, as they often need to be applied in wider contexts in connection with the topics described above, particularly in relation to calculations involving percentage yield and percentage composition.

Coverage begins in *EL* with using relative abundances of isotopes to calculate relative atomic masses. (See the Delivery Guide on Analytical techniques for more on mass spectrometry.)

The concept then moves on to calculations of percentage composition and the ratio by mass of reactants to products in balanced chemical equations, in turn leading to calculations of percentage yield (*EL*) and atom economy (in *'Elements from the Sea', ES*). An appreciation of the differences between percentage yield and atom economy, and their relative merits in assessing the sustainability of a reaction, will be required. The idea of abundances is next revisited in *The ozone story (OZ)* in the context of compositions expressed in parts per million (ppm).

When starting to teach percentage yield, it is important to first establish that learners are comfortable balancing equations and converting between reacting masses and amount of substance.

The calculation for percentage yield is

$$\text{percentage yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100.$$

where the actual and theoretical yield may be expressed in either mass or amount of substance.

The calculation is relatively straightforward, however learners may find it difficult to transfer skills they have learnt in maths GCSE or A level regarding percentages and as such may need reminding. Learners who are unsure of calculating percentages should be led through worked examples at this point in order to understand fully what the equation is asking of them.

Atom economy is calculated as

$$\frac{\text{molecular mass of the desired product}}{\text{sum of molecular masses of all products}} \times 100$$

Learners could be asked to identify the useful product in an equation followed by the calculation of the atom economy.

Titrations

When introducing titration in *EL*, it is useful to separate the theoretical idea of titration from the obfuscations of the practical equipment at first. For example, a simple microscale practical activity where learners count drops of acid needed to neutralise a small volume of alkali, or use plastic pipettes or measuring cylinders to measure volumes, will introduce learners to the ideas of using a known amount of one substance to calculate the amount of another. The uncertainty and unreliability inherent in these techniques would then introduce the need for more specialised and accurate equipment.

Common misconceptions or difficulties learners may have

What is 'amount of substance'?

Historically, the mole was introduced into chemistry well before the concept of 'amount of substance', the quantity for which the mole is the unit. The use of the term 'amount' is unfortunate as it has a more general term in everyday life, and learners often equate the concept of amount to either mass or volume, depending on the context. This adds to the conceptual difficulties in this area.

Confusing amount and mass can be reinforced by phrases such as '12 g of carbon = 1 mol', which are commonly used in textbooks. It is advisable to avoid such phrases as much as possible, as well as similar ones that equate the mole to a volume or a number of particles. Focus on the idea that amount of substance is a separate quantity, which can be *converted* to mass, volume or number of particles through certain formulae. Use clear language to indicate that amount is not the same as e.g. mass, using wording such as '1 mol of carbon atoms *has a mass* of 12 g'.

The incorrect relationship

$$\text{amount} = \frac{\text{mass}}{\text{relative atomic (or molecular) mass}}$$

is still used, but best avoided. Relative atomic mass has no units, so this formula suggests that amount and mass are the same thing. It is far better to always use the term molar mass, *M*, and emphasise its units ($g\ mol^{-1}$). The favoured formula for calculating amount of substance is

$$n = \frac{m}{M}$$

Moles of what?

You need to be clear what the 'fundamental particle' is in any question related to amount of substance. Questions such as "What is the mass of 1 mole of hydrogen?" are at best misleading and at worse counter-productive – it is not clear from this context whether atomic or molecular hydrogen is meant. Best advice is always to use the formula; H and H_2 are unambiguous.

The fundamental unit of an ionic compound

Learners can easily pick up the misconception that ionic compounds consist of discrete 'formula units' and not realise that an ionic formula is the empirical formula for a giant ionic structure. (The same misconception can apply to covalent network structures such as silicon dioxide.)

Using ratio

This is a real 'bête noir' for many learners. The realisation that balanced equations show the ratio by amount of reactants and products can be slow to develop. Much practice is often needed using different starting or finishing amounts.

Concentrations and titration calculations

Ratio again becomes a stumbling block in calculations involving solutions. Some learners have problems understanding how solutions can have a volume that is less (or more) than 1 dm^3, but still have the same concentration measured in mol dm^{-3}. A clear explanation of what the units mean in this case may help: 'mol dm^{-3}' means 'moles per decimetre cubed', and describes the proportion of solute to solvent (in terms of amount per unit of volume). This proportion is the same for any specific quantity of solvent.

Developing this kind of understanding of what units mean can be useful in many other topics to reinforce what a quantity is actually measuring.

Equations and conservation of mass

Despite the relatively straightforward idea of conservation of mass, learners still occasionally manage to get balanced equations wrong, either because they have not balanced the elements on either side or, perhaps more often, the fundamental reactant or product species is wrong. For example, oxygen being written as 'O' (see above point on fundamental particles).

Percentage yield vs atom economy

Atom economy gives information about the efficiency of the reaction whereas percentage yield gives us information about how much product is made. They are different concepts, but learners may not see them as such. The atom economy of a reaction can be improved by

Thinking conceptually

finding a use for the 'waste' products. An example of this is that carbon dioxide produced as a by-product of the petrochemical industry can be used in fizzy drinks or as a substitute for hydrochloric or sulfuric acids in pH adjustment of waste water:

$CO_2 + H_2O \rightarrow H_2CO_3$

$H_2CO_3 + 2NaOH \rightarrow Na_2CO_3 + 2H_2O$

When discussing the question "which is more desirable, a high yield or a high atom economy?" the economics of disposing of a large amount of waste compared with a low percentage yield should be considered.

Conceptual links to other areas of the specification – useful ways to approach this topic to set students up for topics later in the course.

There are strong links to all areas of the specification because of the underpinning nature of this topic area. However some links include:

- titration calculations applied in iodine–thiosulfate titrations in *ES*
- use and understanding of the unit mol in energetics calculations in *DF* and later in *'Oceans' (O)* in the second year of the course
- use and understanding of concentrations in rates of reaction, studied in depth in *The chemical industry (CI)* in the second year of the course
- use and understanding of concentrations in calculations based on equilibrium constants in both *CI* and the *O*. The latter concentrates particularly on acid/base equilibria.

In all of the above specification areas the fundamental idea of 'amount of substance' is built upon in order to be able to understand the particular topic. A good understanding of this concept is therefore vital.

Activities

Learner Activity 1

Balancing chemical equations (PHET at the University of Colorado)
http://phet.colorado.edu/en/simulation/balancing-chemical-equations

For learners who are weak at balancing equations it may be worth starting with some practice in this area. This resource will help with this.

This link is a java applet that can be embedded into virtual learning environments if you so wish. It is a see-saw where learners can move atoms and molecules around to ensure the see saw balances, thus balancing the equation.

Learner Activity 2

How many atoms in my signature? (OCR Lesson Element)
https://www.ocr.org.uk/Images/170200-how-many-atoms-in-my-signature-activity-instructions.pdf

This short activity allows learners to be introduced to amount of substance, the mole and the Avogadro constant using a problem-solving approach.

Learner Activity 3

Apply the mole concept to substances (Richard Thornley)
http://www.youtube.com/watch?v=sM4ulTjsuA4

This is part of a larger series of videos to support IB Chemistry, but the context is relevant to any chemistry course. The series is very well put together and very informative. This video introduces the Avogadro constant and demonstrates the reason the constant has the unit mol·

The whole series is available at https://www.youtube.com/user/richthornley

Learner Activity 4

Mass changes in chemical reactions (Royal Society of Chemistry)
https://edu.rsc.org/resources/mass-changes-in-chemical-reactions/523.article

This Royal Society of Chemistry practical uses a microscale technique to explore the idea of conservation of mass.

Sodium carbonate and calcium nitrate solutions are mixed and any changes in mass noted. The practical then goes on to look at the reaction of marble with hydrochloric acid and learners compare and comment on the results.

(Note: potassium iodide and lead nitrate solutions could be used in the first reaction for a visually more impressive result, and because of the microscale nature the toxicity of the lead compound is much less of a hazard.)

Learner Activity 5

Preparation of magnesium sulfate and calculating the percentage yield (Royal Society of Chemistry, through National STEM Centre)
http://www.nationalstemcentre.org.uk/elibrary/resource/10982/milk-of-magnesia-extemporaneous-preparation

This experiment is part of an activity impressively named 'Milk of Magnesia Extemporaneous Preparation' from the Royal Society of Chemistry's Advancing the Chemical Sciences collection.

Hydrated magnesium sulfate is prepared from magnesium oxide and excess sulfuric acid.

Learner Activity 6

Finding the formula of copper oxide (Royal Society of Chemistry)
https://edu.rsc.org/resources/finding-the-formula-of-copperii-oxide/727.article

This practical uses methane to reduce copper oxide to copper. Learners measure the masses of the oxide and the final copper and determine the formula of the original oxide.

Learner Activity 7

Calculating percentage yield (Cavalcade Publishing)
http://misterguch.brinkster.net/PRA022.pdf

This is a worksheet with answers that would help learners reinforce the calculations required for percentage yield..

Learner Activity 8

A redox titration (Hodder Education, through National STEM Centre)
http://www.nationalstemcentre.org.uk/elibrary/resource/7611/unit-s1-the-mole

The purpose of Experiment 4 in this resource is to balance the equation for the reaction of iodine with sodium thiosulfate solution by titration.

Learner Activity 9

The volume of one mole of hydrogen gas (Royal Society of Chemistry)
http://www.nationalstemcentre.org.uk/elibrary/resource/9688/the-volume-of-one-mole-of-hydrogen-gas

Learners react magnesium quantitatively with hydrochloric acid. They collect the hydrogen and calculate the molar volume.

Learner Activity 10

The difference between percentage yield and atom economy (Frank Harriss)
https://www.youtube.com/watch?v=9YpT-QGTrWw

This is a 10-second animation showing the difference between percentage yield and atom economy. The percentage yield animation shows that a high yield could lead to more waste and so a poor atom economy. In contrast, the atom economy animation shows no waste, but not necessarily a high yield. The animation could be embedded into a PowerPoint as a starter or a talking point. A possible starter could include the question "Why would a high yield not necessarily be good for the environment?"

Thinking contextually

Understanding the mole concept is fundamental for adding the quantitative dimension to chemistry and therefore appears in a wide range of content within the specification and can be taught in many contexts.

Early applied contexts include calculating the amount of different elements in the body from mass data in *EL*. An interesting follow-up to this idea in *DM* looks at the percentage carbon impurity in 'pig iron' in terms of both mass and amount of substance.

Other contexts include:

- the formation of salts, found in our bodies and the sea, and calculating the concentration of these salts via titration (*EL*)
- calculating the volume of pollutant gases from the combustion of different fuels (*DF*)
- industrial methods for the manufacture of chlorine and their atom economies (*CI*)
- calculating the solubility of sparingly soluble compounds, such as the shells of some marine organisms (*O*).

Atom economy is introduced in *ES* in the context of the formation of hydrochloric acid. Percentage yield is not discussed at this point, but could be revisited and compared to atom economy. Ideas discussed here could then be revisited in *CI* in the second year, when discussing the merits of different industrial processes, as well as in the context of evaluating organic syntheses in *What's in a medicine (WM)* and *Colour by design (CD)*. For example, addition reactions always have a 100% atom economy because they only have one product. Substitution reactions don't have 100% atom economy as there is more than one product.

Percentage yield is introduced in *EL* in the context of inorganic reactions, and may be revisited in the context of equilibrium in *ES*. However, the concept is excellently reinforced when conducting organic synthesis in *WM* and *CD*.

Learner Activity 1

Finding how much salt there is in sea water (Royal Society of Chemistry, through National STEM Centre)
http://www.nationalstemcentre.org.uk/elibrary/resource/9590/finding-out-how-much-salt-there-is-in-seawater

An interesting microscale titration to determine the concentration of chloride ion in sea water.

Learner Activity 2

Heats of reaction (Royal Society of Chemistry)
https://edu.rsc.org/experiments/exothermic-or-endothermic/406.article

This experiment looks at a number of reactions, both exothermic and endothermic, and learners determine the enthalpy change per mole of reaction. ICT (data logging) can also be used in this experiment. This practical reinforces ideas met with in *DF*.

Learner Activity 3

Green chemistry, atom economy and sustainable development (Royal Society of Chemistry)
https://edu.rsc.org/download?ac=15080

An excellent resource that links yield, atom economy and sustainability into one well-structured worksheet. It provides descriptions and questions relating to each concept, and discusses the relevance of each to assessing the sustainability of chemical processes.

Learner Activity 4

Determining the value of an equilibrium constant (Hodder Education, through National STEM Centre)
http://www.nationalstemcentre.org.uk/elibrary/resource/7646/unit-p2-equilibrium-i-principles

The purpose of this experiment is to calculate the equilibrium constant for the reaction between ethyl ethanoate and water. Equilibrium constants are introduced in *ES*.

The resource is part of John Murray, Independent Learning Project for Advanced Chemistry (ILPAC); ILPAC Physical Chemistry Unit P2: Equilibrium I: Principles

Learner Activity 5

Atom economy (Aus-e-tute)
http://www.ausetute.com.au/atomeconomy.html

This is an online tutorial which runs through the calculation of atom economy, looking at the atom economies of two different synthesis routes for bromoethane. It could form part of a student revision site perhaps on a virtual learning environment.

Learner Activity 6

Calculating percentage yield (www.4college.co.uk)
http://www.4college.co.uk/a/Md/yield.php

An example of a resource that could be used to calculate percentage yield, set in the context of organic reactions. It provides a step by step demonstration of the calculation.

Learner Activity 7

Ibuprofen – a case study in green chemistry (Royal Society of Chemistry)
http://www.ch.ic.ac.uk/marshall/4I6/Ibuprofen2.pdf

This is a structured worksheet which incorporates percentage yield and atom economy based around the synthesis of ibuprofen. It also covers many concepts relating to organic synthesis. It will need to be differentiated according to ability of the students – parts could be taken away or added. It could also be used as a stretch and challenge activity.

Learner Activity 8

Determining the solubility and solubility product of calcium hydroxide (Hodder Education, through National STEM Centre)
http://www.nationalstemcentre.org.uk/elibrary/resource/7646/unit-p2-equilibrium-i-principles

Calcium hydroxide is only sparingly soluble and the concentration of hydroxide ions can be determined by titration with hydrochloric acid; the concentration of calcium ions can be calculated from the titration result. This quantitative experiment supports and reinforces ideas met in the A Level unit *'Oceans' (O)*

The resource is part of John Murray, Independent Learning Project for Advanced Chemistry (ILPAC); ILPAC Physical Chemistry Unit P2: Equilibrium I: Principles

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