Purple fumes: the importance of iodine

Iodine, with its characteristic purple vapours, has myriad applications – from the familiar disinfectant to innovative solar cells.

What makes iodine so important and interesting? Not only does it sublimate into a dramatic purple gas, but it also affects many aspects of life on Earth and of human civilisation. Did you know, for example, that iodine protects marine algae from oxidative damage (for example from the Sun), prevents some congenital abnormalities in humans, and has many industrial applications?

The discovery of iodine can be traced back to the 19th century and the Napoleonic wars. With the British imposing a blockade on European ports, the French were faced with shortages of saltpetre (KNO₃) for manufacturing gunpowder. So chemist Bernard Courtois investigated the potential of seaweed (brown algae, Laminaria sp.) as the potassium source for this crucial substance. He added concentrated sulphuric acid to seaweed ash and was surprised by the beautiful purple fumes that were produced (figure 1).

Although Courtois suspected that his purple vapour was a new element, he did not have the financial means to follow up his research. It was left to his colleagues, including Joseph Gay-Lussac, to confirm his results and name the element iodine, from the Greek word iōdes, which means purple or violet.

Gay-Lussac went on to investigate the chemistry of iodine, and despite the war, the French chemists found ways to correspond with British chemists, notably Sir Humphry Davy. Initially, Davy believed the vapour to be a chlorine compound, but soon concluded that it was indeed a new element.
In this concise update on the element iodine, the authors guide the reader through the history and the many applications of this important element, from medicine to industry and energy production. Suggestions for school laboratory experiments add interest and appeal to the topic.

Given the plain and clear style, I recommend this article not only to European science teachers but also to their students aged 13-18. It could be used in lessons on chemistry (the periodic table, halogens), biology (endocrine glands, the thyroid and its diseases) and physics (isotopes, radioactivity and solar cells). There is also an interdisciplinary opportunity to address the history of science (the discovery of the elements), the role of scientists in the development of weapons, or the relationships between scientists of opposing countries during wartime.

Suitable comprehension questions include:

1. From the article you can deduce that seaweeds accumulate iodine:
   a) To oxidise atmospheric ozone 
   b) To absorb atmospheric ozone 
   c) To produce atmospheric ozone 
   d) To protect themselves from atmospheric ozone.

2. If we do not receive enough iodine:
   a) Our thyroid gland enlarges / atrophies 
   b) Our anterior pituitary gland secretes less / more thyroid-stimulating hormone
With the help of X-ray absorption spectroscopy, we now know that seaweeds accumulate iodine as iodide ($I^-$), which acts as an antioxidant to protect them against oxidative damage caused by atmospheric ozone ($O_3$). This goes some way to explaining why trace amounts of molecular iodine ($I_2$) can be detected in the atmosphere of coastal regions and why human iodine intake in these regions is dependent on seaweed abundance rather than proximity to the sea.

For much of the next century, iodine continued to be extracted from seaweed. Today, however, it is removed from natural iodine-containing brines in gas and oil fields in Japan and the USA, or from Chilean caliches (nitrate ores), which contain calcium iodate ($Ca(IO_3)_2$). The iodine is supplied to the market as a purplish-black solid.

**Iodine chemistry**

Iodine belongs to the halogens, and thus shares many of the typical characteristics of the elements in this group. Because of its high electronegativity, iodine forms iodides with most elements in its formal oxidation state, -1. Many iodine-containing compounds are frequently used as reagents in organic synthesis – mainly for iodination, oxidation and C-C bond formation.

Iodine in the atmosphere originates mostly from biological and chemical processes in the ocean – such as the iodide antioxidant system in seaweeds. Most iodine is ultimately removed from the atmosphere by cloud formation. In the ocean, iodine is mainly dissolved and exists as iodate ($IO_3^-$, oxidised form) and iodide ($I^-$, reduced form). In Earth’s outer layer (the lithosphere), most iodine is in marine and terrestrial sediments; iodine levels are low in igneous rocks.

**The physiological importance of iodine**

Physiologically, iodine is an essential element, required for the synthesis
of thyroid hormones – triiodothyronine and thyroxine (figure 3) – which regulate growth, development and cell metabolism. The recommended dietary intake of iodine for adults is 150 µg/day, which can be obtained from dairy products, seaweed and iodised table salt.

The classic symptom of iodine deficiency is thyroid enlargement (goitre). As iodine intake falls, the anterior pituitary gland secretes increasing levels of thyroid-stimulating hormone in an effort to maximise the uptake of available iodine; this leads to excessive growth of the thyroid gland. But the most damaging effect of a lack of iodine is to the developing brains of babies, leading to mental retardation. Furthermore, severe iodine deficiency during pregnancy is associated with a greater incidence of stillbirth, miscarriage and congenital abnormalities.

The most effective way to prevent iodine deficiency is to add potassium...
Iodine is used in one of the most promising solar cells on the market for the production of low-cost ‘green energy’: the dye-sensitised titanium oxide solar cell. Also known as the Grätzel cell after one of its inventors, it consists of polyiodide electrolytes as the charge transport layer between the cathode and the anode (to learn more, see Shallcross et al., 2009).

Of the 37 known isotopes of iodine, all but one, 127I, are radioactive. Most of these radioisotopes, which are produced via fission reactions in nuclear power plants and weapons, are short-lived, which makes them useful as tracers and therapeutic agents in medicine. For example, iodine isotopes can be used to image the thyroid gland, which absorbs radioactive iodine when it is injected into the bloodstream.

Unfortunately, radioactive 131I, released from nuclear accidents – such as the disaster in Fukushima, Japan, in 2011 – is also taken up by the thyroid. Because it is a high-energy β-particle, iodide (KI) or potassium iodate (KIO₃) to table salt. This practice of salt iodisation is carried out in around 120 countries, with more than 70% of the world population now having access to iodised salt.

**Industrial uses of iodine**

Iodine and its compounds are used in myriad products, from food and pharmaceuticals, through to animal feed and industrial catalysts (figure 4). For instance, iodine is a potent antimicrobial. For more than a century, iodine tincture – a mixture of ethanol, water, iodine and potassium iodide – was used as an antiseptic for wounds. This has now largely been replaced by water-soluble ionophores (iodine complexed with surfactants), which are less irritating to the skin. For example, povidone iodine, a mixture of polyvinylpyrrolidone and iodine, is used widely as a surgical scrub.

In the industrial production of acetic acid, iodine compounds such as rhodium iodide (the Monsanto process) or iridium iodide (BP’s Cativa process) are used to catalyse the carbonylation of methanol.

Silver iodide (AgI), used in early photographic plates, is used today in cloud seeding to initiate rain and to control climate. Because AgI has a similar crystal structure to ice, it can induce freezing by providing nucleation sites. This was done at the 2008 Beijing Olympics to prevent rainfall during the opening and closing ceremonies.

With its high atomic weight (126.9) and large number of electrons, iodine is also an excellent X-ray absorber and is used in X-ray contrast media. These substances are generally safe to administer to humans and enable the visualisation of soft tissues in X-ray examinations.

A more everyday application of iodine is in liquid-crystal displays for TVs, computers and mobile phones, which use polarising films to filter light. These films are commonly made of polyvinyl alcohol layers doped with iodine. Here, iodine acts as a cross-linker and ensures that the structure is polarising.

**Iodine in the energy industry**

Iodine is used in one of the most promising solar cells on the market for the production of low-cost ‘green energy’: the dye-sensitised titanium oxide solar cell. Also known as the Grätzel cell after one of its inventors, it consists of polyiodide electrolytes as the charge transport layer between the cathode and the anode (to learn more, see Shallcross et al., 2009).

Of the 37 known isotopes of iodine, all but one, 127I, are radioactive. Most of these radioisotopes, which are produced via fission reactions in nuclear power plants and weapons, are short-lived, which makes them useful as tracers and therapeutic agents in medicine. For example, iodine isotopes can be used to image the thyroid gland, which absorbs radioactive iodine when it is injected into the bloodstream.

Unfortunately, radioactive 131I, released from nuclear accidents – such as the disaster in Fukushima, Japan, in 2011 – is also taken up by the thyroid. Because it is a high-energy β-particle, iodide (KI) or potassium iodate (KIO₃) to table salt. This practice of salt iodisation is carried out in around 120 countries, with more than 70% of the world population now having access to iodised salt.

**Industrial uses of iodine**

Iodine and its compounds are used in myriad products, from food and pharmaceuticals, through to animal feed and industrial catalysts (figure 4). For instance, iodine is a potent antimicrobial. For more than a century, iodine tincture – a mixture of ethanol, water, iodine and potassium iodide – was used as an antiseptic for wounds. This has now largely been replaced by water-soluble ionophores (iodine complexed with surfactants), which are less irritating to the skin. For example, povidone iodine, a mixture of polyvinylpyrrolidone and iodine, is used widely as a surgical scrub.

In the industrial production of acetic acid, iodine compounds such as rhodium iodide (the Monsanto process) or iridium iodide (BP’s Cativa process) are used to catalyse the carbonylation of methanol.

Silver iodide (AgI), used in early photographic plates, is used today in cloud seeding to initiate rain and to control climate. Because AgI has a similar crystal structure to ice, it can induce freezing by providing nucleation sites. This was done at the 2008 Beijing Olympics to prevent rainfall during the opening and closing ceremonies.

With its high atomic weight (126.9) and large number of electrons, iodine is also an excellent X-ray absorber and is used in X-ray contrast media. These substances are generally safe to administer to humans and enable the visualisation of soft tissues in X-ray examinations.

A more everyday application of iodine is in liquid-crystal displays for TVs, computers and mobile phones, which use polarising films to filter light. These films are commonly made of polyvinyl alcohol layers doped with iodine. Here, iodine acts as a cross-linker and ensures that the structure is polarising.

**Iodine in the energy industry**

Iodine is used in one of the most promising solar cells on the market for the production of low-cost ‘green energy’: the dye-sensitised titanium oxide solar cell. Also known as the Grätzel cell after one of its inventors, it consists of polyiodide electrolytes as the charge transport layer between the cathode and the anode (to learn more, see Shallcross et al., 2009).

Of the 37 known isotopes of iodine, all but one, 127I, are radioactive. Most of these radioisotopes, which are produced via fission reactions in nuclear power plants and weapons, are short-lived, which makes them useful as tracers and therapeutic agents in medicine. For example, iodine isotopes can be used to image the thyroid gland, which absorbs radioactive iodine when it is injected into the bloodstream.

Unfortunately, radioactive 131I, released from nuclear accidents – such as the disaster in Fukushima, Japan, in 2011 – is also taken up by the thyroid. Because it is a high-energy β-particle, iodide (KI) or potassium iodate (KIO₃) to table salt. This practice of salt iodisation is carried out in around 120 countries, with more than 70% of the world population now having access to iodised salt.

**Industrial uses of iodine**

Iodine and its compounds are used in myriad products, from food and pharmaceuticals, through to animal feed and industrial catalysts (figure 4). For instance, iodine is a potent antimicrobial. For more than a century, iodine tincture – a mixture of ethanol, water, iodine and potassium iodide – was used as an antiseptic for wounds. This has now largely been replaced by water-soluble ionophores (iodine complexed with surfactants), which are less irritating to the skin. For example, povidone iodine, a mixture of polyvinylpyrrolidone and iodine, is used widely as a surgical scrub.

In the industrial production of acetic acid, iodine compounds such as rhodium iodide (the Monsanto process) or iridium iodide (BP’s Cativa process) are used to catalyse the carbonylation of methanol.

Silver iodide (AgI), used in early photographic plates, is used today in cloud seeding to initiate rain and to control climate. Because AgI has a similar crystal structure to ice, it can induce freezing by providing nucleation sites. This was done at the 2008 Beijing Olympics to prevent rainfall during the opening and closing ceremonies.

With its high atomic weight (126.9) and large number of electrons, iodine is also an excellent X-ray absorber and is used in X-ray contrast media. These substances are generally safe to administer to humans and enable the visualisation of soft tissues in X-ray examinations.

A more everyday application of iodine is in liquid-crystal displays for TVs, computers and mobile phones, which use polarising films to filter light. These films are commonly made of polyvinyl alcohol layers doped with iodine. Here, iodine acts as a cross-linker and ensures that the structure is polarising.

**Iodine in the energy industry**

Iodine is used in one of the most promising solar cells on the market for the production of low-cost ‘green energy’: the dye-sensitised titanium oxide solar cell. Also known as the Grätzel cell after one of its inventors, it consists of polyiodide electrolytes as the charge transport layer between the cathode and the anode (to learn more, see Shallcross et al., 2009).

Of the 37 known isotopes of iodine, all but one, 127I, are radioactive. Most of these radioisotopes, which are produced via fission reactions in nuclear power plants and weapons, are short-lived, which makes them useful as tracers and therapeutic agents in medicine. For example, iodine isotopes can be used to image the thyroid gland, which absorbs radioactive iodine when it is injected into the bloodstream.

Unfortunately, radioactive 131I, released from nuclear accidents – such as the disaster in Fukushima, Japan, in 2011 – is also taken up by the thyroid. Because it is a high-energy β-particle, iodide (KI) or potassium iodate (KIO₃) to table salt. This practice of salt iodisation is carried out in around 120 countries, with more than 70% of the world population now having access to iodised salt.
emitter, it damages cells and induces cancer. To counteract this effect, non-radioactive potassium iodide (KI) tablets are ingested to saturate the thyroid’s ability to take up radioactive iodine.

These are just a small sample of the many applications of iodine. Clearly, although the element has been known for only two hundred years, it is well established in modern chemistry, physics and medicine.

Acknowledgement

This article was adapted from a much longer publication in *Angewandte Chemie International Edition* (Küpper et al., 2011).

References


Iodine in the classroom

No doubt we are all familiar with the colourful ‘iodine clock’ experiment between hydrogen peroxide, potassium iodide, starch and sodium thiosulphate – but there are many other ways to introduce iodine practically into the classroom. For example:

- When catalysed by water, aluminium and iodine react to produce spectacular clouds of purple iodine vapour.
- In a direct reaction between a metal and a non-metal, zinc powder reacts with a solution of iodine in ethanol to form zinc iodide in an exothermic redox reaction.

- Potassium iodide can be used to detect the presence of starch in a range of foods.
- Various solutions, including aqueous sodium iodide, can be electrolysed and the products at the electrodes identified. Students can then use their practical experience and theoretical knowledge to construct simple ionic equations.

Details of these and many other school experiments can be downloaded from the Learn Chemistry website.
Chemistry

Shozo Yanagida is a professor at the Center for Advanced Science and Innovation, Osaka University, Japan. His research focuses on dye-sensitised solar cells.

Michael B Zimmermann MD is a professor of human nutrition at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland. His research focuses on the disorders caused by iodine deficiency. He teaches several courses on nutrition and metabolism at the University, at both undergraduate and graduate level.

Berit Olofsson is a professor of organic chemistry at Stockholm University, Sweden. Her research focuses on hypervalent iodine chemistry, which involves iodine compounds in high oxidation states. She has given several popular scientific lectures to secondary-school students to stimulate their interest in chemistry.

Dr Tatsuo Kaiho is the director of Nihon Tennen Gas Co Ltd, Japan. His research interests are iodine production and its novel applications.

Dr Tatsuo Kaiho is the director of Nihon Tennen Gas Co Ltd, Japan. His research interests are iodine production and its novel applications.

Frithjof C Küpper is a professor of marine biodiversity at the University of Aberdeen, UK. His research focuses on the biochemistry and biodiversity of marine algae and microbes – in particular, on halogen metabolism of seaweeds and its atmospheric impact. He is engaged in a range of scientific outreach activities, recently including the production of a filmed documentary (Immersed in the Arctic).

Martin C Feiters is an associate professor in the Institute for Molecules and Materials at the Radboud University Nijmegen, the Netherlands. He has been involved in many spectroscopic and structural studies involving synchrotron radiation, and in chemistry demonstrations for secondary-school students who are interested in studying science further.

Potassium iodide pills are distributed to people living within a radius of 10 km of each nuclear power plant in France, to prevent damage to their thyroid glands in case of an accident.

This Cessna 210 plane has two silver iodide generators on the sides for cloud seeding.

[Image of the Cessna 210 plane with silver iodide generators]

Image courtesy of Christian Jansky / Wikimedia

Image courtesy of the Pharmacie Centrale des Armées

Web reference

w1 – The Learn Chemistry website of the UK’s Royal Society of Chemistry offers a wide range of downloadable resources to support the teaching and learning of chemistry. See: www.rsc.org/learn-chemistry

Frithjof C Küpper is a professor of marine biodiversity at the University of Aberdeen, UK. His research focuses on the biochemistry and biodiversity of marine algae and microbes – in particular, on halogen metabolism of seaweeds and its atmospheric impact. He is engaged in a range of scientific outreach activities, recently including the production of a filmed documentary (Immersed in the Arctic).

Martin C Feiters is an associate professor in the Institute for Molecules and Materials at the Radboud University Nijmegen, the Netherlands. He has been involved in many spectroscopic and structural studies involving synchrotron radiation, and in chemistry demonstrations for secondary-school students who are interested in studying science further.

Berit Olofsson is a professor of organic chemistry at Stockholm University, Sweden. Her research focuses on hypervalent iodine chemistry, which involves iodine compounds in high oxidation states. She has given several popular scientific lectures to secondary-school students to stimulate their interest in chemistry.

Dr Tatsuo Kaiho is the director of Nihon Tennen Gas Co Ltd, Japan. His research interests are iodine production and its novel applications.

Shozo Yanagida is a professor at the Center for Advanced Science and Innovation, Osaka University, Japan. His research focuses on dye-sensitised solar cells.

Michael B Zimmermann MD is a professor of human nutrition at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland. His research focuses on the disorders caused by iodine deficiency. He teaches several courses on nutrition and metabolism at the University, at both undergraduate and graduate level.
The nuclear power plant at Tricastin, France, is situated close to a densely populated region. Approximately every five years, potassium iodide pills are distributed to the people who live nearby to prevent damage to their thyroid glands in case of a nuclear accident.

Lucy J Carpenter is a professor of atmospheric chemistry at the University of York, UK. Her specialities are volatile halogens and their influence on atmospheric chemistry.

George W Luther is the Harrington Professor of Marine Chemistry at the School of Marine Science & Policy at the University of Delaware, USA. He explores biogeochemical processes in marine environments, emphasising research that interfaces chemistry with biology with the view that chemistry drives biology. He performs chemical magic shows for local schools and outreach programmes, and takes high-school teachers on oceanographic research cruises, including those studying hydrothermal vents.

Zunli Lu is an assistant professor at Syracuse University, NY, USA, and specialises in geological cycling of iodine.

Mats Jonsson is a professor of nuclear chemistry at the Royal Institute of Technology, in Stockholm, Sweden.

Lars Kloo is a professor of inorganic chemistry and the head of applied physical chemistry at the Royal Institute of Technology (KTH), in Stockholm, Sweden. He is often involved with school teachers and their classes, on the subject of solar energy in general and solar cells in particular. Currently, he is involved in the Soljakten programme, jointly with the Nobel Museum, in Stockholm, which is aimed at final-year elementary-school classes.
Safety note
For all of the activities published in Science in School, we have tried to check that all recognised hazards have been identified and that suitable precautions are suggested. Readers should be aware, however, that errors and omissions can be made, and safety standards vary across Europe and even within individual countries.
Therefore, before undertaking any activity, readers should always carry out their own risk assessment. In particular, any local rules issued by employers or education authorities must be observed, whatever is suggested in the Science in School articles.
Unless the context dictates otherwise, it is assumed that:
- Practical work is carried out in a properly equipped and maintained science laboratory.
- Any electrical equipment is properly maintained.
- Care is taken with normal laboratory operations such as heating.
- Good laboratory practice is observed when chemicals or living organisms are used.
- Eye protection is worn whenever there is any recognised risk to the eyes.
- Pupils and/or students are taught safe techniques for activities involving living organisms, hazardous materials and equipment.

Credits
Science in School is a non-profit activity. Initially supported by the European Commission, it is now funded by EIROforum.

Disclaimer
Views and opinions expressed by authors and advertisers are not necessarily those of the editors or publisher. We are grateful to all those who volunteer to translate articles for the Science in School website (see the guidelines on our website). We are, however, unable to check the individual translations and cannot accept responsibility for their accuracy.

Copyright
With very few exceptions, articles in Science in School are published under Creative Commons copyright licences allow the text to be reused non-commercially. Note that the copyright licences refer to the text of the articles and not to the images. You may republish the test according to the following licences, but you may not reproduce the images without the consent of the copyright holder.

Most Science in School articles carry one of two copyright licences:

1) Attribution Non-commercial Share Alike
No Endorsement (by-nc-sa-nc):
This licence lets you remix, tweak, and build upon the author’s work non-commercially, as long as you credit the author and licence their new creations under the identical terms. You can download and redistribute the author’s work, but you can also translate or produce new articles based on the work. All new work based on the author’s work will carry the same licence, so any derivatives will also be non-commercial in nature.
Furthermore, you may not imply that the derivative work is endorsed or approved by the author of the original work or by Science in School.

2) Attribution Non-commercial No Derivatives (by-nc-nd):
This licence is often called the ‘free advertising’ licence because although you can reproduce the author’s works and share them with others as long as you mention and link back to the author, you cannot change them in any way or use them commercially.
For further details, see: http://creativecommons.org/licenses
All articles in Science in School carry the relevant copyright logos or other copyright notice.
How many schools and teachers do you reach worldwide?

Advertising in Science in School
- Choose between advertising in the quarterly print journal or on our website.
- Website: reach over 30,000 science educators worldwide - every month.
- In print: target over 5000 European science educators every quarter, including over 3500 named subscribers.
- Distribute your flyers, brochures, CD-ROMs or other materials to the recipients of the print copies.

For more details, see www.scienceinschool.org/advertising