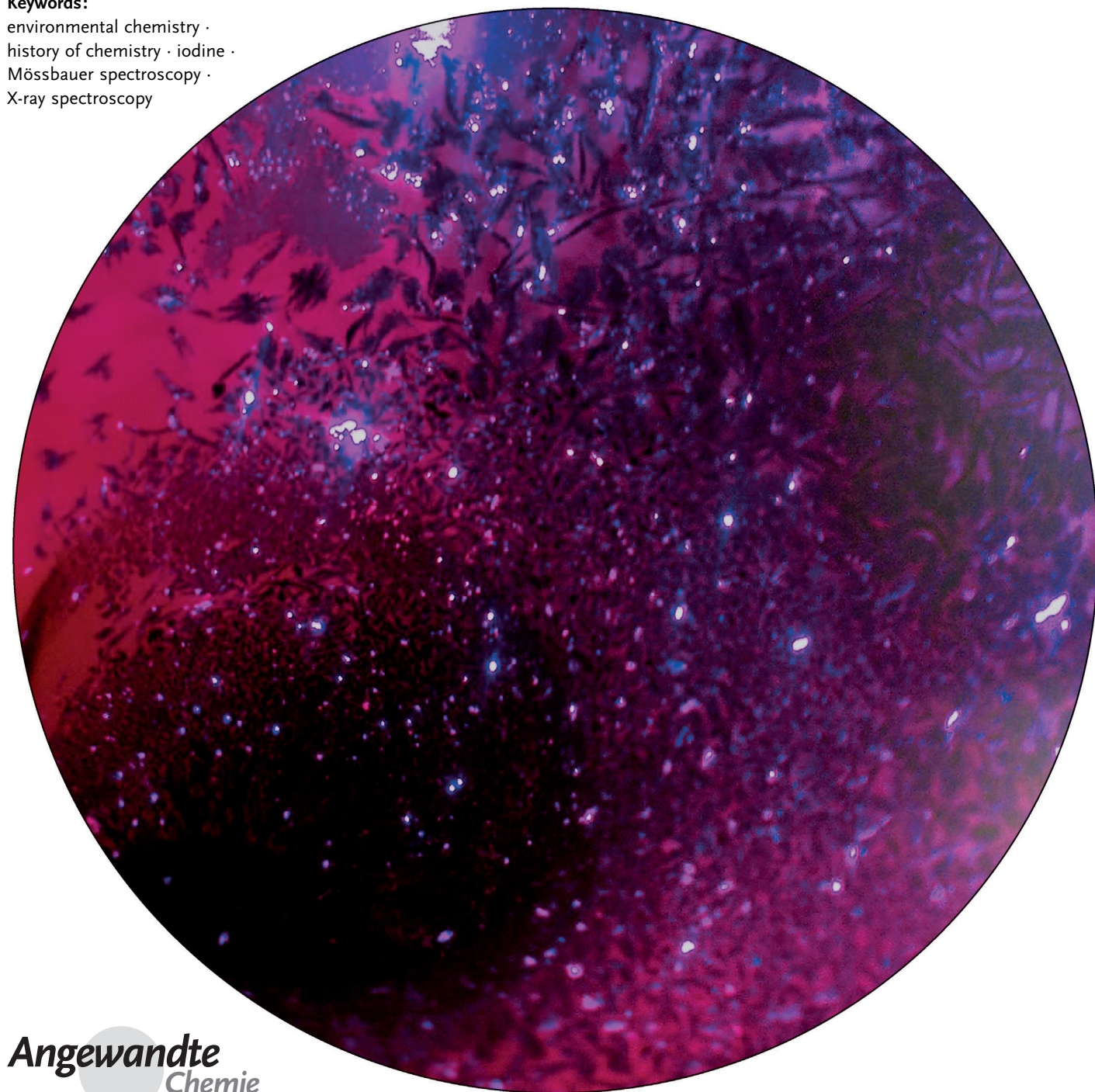


Commemorating Two Centuries of Iodine Research: An Interdisciplinary Overview of Current Research

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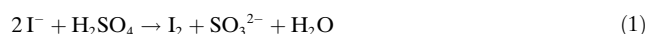
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Mössbauer spectroscopy ·
X-ray spectroscopy



Iodine was discovered as a novel element in 1811 during the Napoleonic Wars. To celebrate the bicentennial anniversary of this event we reflect on the history and highlight the many facets of iodine research that have evolved since its discovery. Iodine has an impact on many aspects of life on Earth as well as on human civilization. It is accumulated in high concentrations by marine algae, which are the origin of strong iodine fluxes into the coastal atmosphere which influence climatic processes, and dissolved iodine is considered a biophilic element in marine sediments. Iodine is central to thyroid function in vertebrates, with paramount implications for human health. Iodine can exist in a wide range of oxidation states and it features a diverse supramolecular chemistry. Iodine is amenable to several analytical techniques, and iodine compounds have found widespread use in organic synthesis. Elemental iodine is produced on an industrial scale and has found a wide range of applications in innovative materials, including semiconductors—in particular, in solar cells.

1. Historic Background

The goiter-preventing effects of iodine in seaweeds were known to the legendary Chinese emperor Shen-Nung as early as around 3000 BC, and the knowledge of this treatment was available in Greece by the time of Hippocrates.^[1] Nevertheless, iodine was not isolated and recognized as an element until an early 19th century chemist, Bernard Courtois, explored brown seaweeds (*Laminaria* sp., *Fucus* sp.; Figure 1) for their potential as an alternative feedstock to wood ashes for the production of saltpeter that was required for the Napoleonic war effort.^[2] The addition of concentrated sulfuric acid to seaweed ashes did not only result in strong corrosion of his copper vessels, he also noticed the emission of a previously unobserved violet vapor through the reaction shown in Equation (1).



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Unfortunately, Courtois could not follow up on his research of this new substance because of economic hardship. However, he managed to incite two of his chemist friends, Charles Bernard Desormes and Nicolas Clément, to pursue the studies—together with André M. Ampère and Joseph Louis Gay-Lussac. Clément presented the findings on Courtois' behalf to the Imperial Institute of France (*Conservatoire des Arts et Métiers*, where he held a professorship) on November 29, 1813, which resulted in their original

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Figure 1. Brown algae, especially of the genus *Laminaria* sp., are the strongest iodine accumulators among all living systems. They use iodide as a simple, inorganic antioxidant. At low tide, high iodide concentrations at the algal surface react with atmospheric oxidants, such as ozone, thereby resulting in strong fluxes of molecular iodine into the coastal atmosphere which contribute to the formation of aerosols. (Photograph: F.C.K., taken on the shore at Dunstaffnage, near Oban, Scotland, at low tide.)

publication in the *Annales de Chimie* (Figure 2).^[3] This paper already uses the name *iode* for the new substance, “due to the beautiful violet color of its vapor” (from the Greek *ιώδης* or *ιοειδής*, that is, violet) and mentions the metal-like appearance of its solid, elemental state. Shortly afterwards, on December 6 and 20 of the same year, Gay-Lussac presented his results on the compounds that this novel element formed with other elements.^[4] It is amazing that despite the war, in which most of Europe was embroiled at that time, scientific exchange between opposing powers was still functioning. The eminent British chemist Sir Humphry Davy corresponded with his French peers (with mail taken back and forth between the hostile countries by smugglers and cartels), and was given free passage to France (with Napoleon’s personal approval). Ampère gave him a sample of the new substance so that he could conduct his own research on iodine (Davy was traveling with a portable chest for chemical experiments). Initially, Davy believed that it was merely a compound of



Frithjof C. Küpper was recently appointed to the Chair in Marine Biodiversity, a full professorship at the University of Aberdeen. Until then, he was a Reader in Algal Biochemistry at the Scottish Association for Marine Science. He obtained a joint French–German PhD with Bernard Kloareg (Roscoff) and Dieter G. Müller (Konstanz), and carried out postdoctoral research with Alison Butler (Santa Barbara). Leading an international consortium, his research has resulted in the finding of iodide serving as an inorganic antioxidant in kelp, the first described from a living system.

Découverte d'une substance nouvelle dans le Vareck.

PAR M. B. COURTOIS (1).

Les eaux-mères des lessives de Vareck contiennent en assez grande quantité une substance bien singulière et bien curieuse ; on l'en retire avec facilité : il suffit de verser de l'acide sulfurique sur ces eaux-mères et de chauffer le tout dans une cornue dont le bec est adapté à une alonge, et celle-ci à un ballon. La substance qui s'est précipitée sous la forme d'une poudre noire-brillante, aussitôt après l'addition de l'acide sulfurique, s'élève en vapeur d'une superbe couleur violette quand elle éprouve la chaleur ; cette vapeur se condense dans l'alonge et dans le récipient, sous la forme de lames cristallines très-brillantes et d'un éclat égal à celui du plomb sulfuré cristallisé ; en lavant ces lames avec un peu d'eau distillée, on obtient la substance dans son état de pureté.

(1) Cette découverte a été annoncée le 6 décembre, à la séance de la première classe de l'Institut, par M. Clément.

Figure 2. The front page of Courtois' historic publication reporting the discovery of iodine.

chlorine, but came to the conclusion that it was an element in its own right,^[5] and competed for a while with Gay-Lussac over priority rights (even though both Davy and Gay-Lussac always acknowledged Courtois as the discoverer of iodine). Despite the scientific fame of the discovery and the rising commercial interest in iodine, for example, for the treatment of wounds, Courtois failed to capitalize on his discoveries and, sadly, died in poverty on September 27, 1838, aged only 62.^[6] Iodine production from seaweeds became a major economic activity in the coastal regions of Europe, in particular in parts of Brittany, Normandy, Ireland, and Scotland, and it features in many historic and travel accounts of these places (for example, Ref. [7]).

2. Characteristic Chemistry

Iodine belongs to Group 17 of the Periodic Table, the halogens, and thus shares many of the typical characteristics of the elements in this group, such as high electronegativity (2.66 according to the Pauling scale) and a valence p^{n-1} configuration. These properties make iodine highly reactive and prone to radical reactions. As a consequence of its high electronegativity it forms iodides with most elements, with iodine possessing the formal oxidation state $-I$. Iodine is known in compounds with formal oxidation states ranging from $-I$ to $+VII$. The high formal positive oxidation states

are mainly found in compounds with the very electronegative elements oxygen and fluorine. However, since the polarizability of iodine is quite high, the chemical bonds also formed with the more electropositive elements in the Periodic Table tend to contain a fair degree of covalency. This makes the structural chemistry of iodide compounds a bit more complex than for the other halogens. Just as for its halogen congeners, molecular compounds are formed when the difference in electronegativity is small, but for larger differences chain- and layer-type of structures are also frequently observed, rather than simple ionic compounds controlled only by ion electrostatics and ion size. Well-known and representative examples include AuI (chainlike structure), CdI₂ (layered structure), and ReI₃ (chainlike structure of Re₃I₉ units). It is also notable that iodides of highly charged cations tend to be unstable because of reduction, where iodide loses its valence electron to form neutral iodine. Similar to the other halogens, the valence-electron configuration renders I₂ molecules the stable state of the element under ambient conditions, with a direct and single I–I bond. The I₂ molecule is well known to form charge-transfer compounds with a large number of reactants, in which iodine acts as an electron-density acceptor (Lewis acid), for example, with aromatic molecules. With strong nucleophilic donors, such as organic amines, iodine tends to split heterolytically to form I[−] ions. Both heterolytic and homolytic cleavage is observed in alkylation reactions, in which alkyl iodides constitute very useful reactants for synthesis. In everyday life, iodine is probably best known for its use as a disinfectant in aqueous solution (tincture of iodine).

3. Supramolecular Interactions of Iodine, Iodide, and Iodocarbons

In solution, I₂ typically accepts electrons from the solvent molecule (Figure 3) into its lowest unoccupied molecular orbital (LUMO). This lowers the energy of the transition from the highest occupied molecular orbital (HOMO) of the iodine atom to its LUMO, thereby changing the color from the characteristic violet to brown and other colors. Depending on the electron-donating ability of the solvent, absorption bands are observed from 520–540 nm in hydrocarbon and chlorocarbon solvents, to 490–510 nm in aromatic solvents, and 450–480 nm in alcohols and amines.^[8] With very good electron donors, such as triphenylphosphine and pyridine, charge-transfer complexes of the type [Ph₃P–I]⁺I[−] and [pyr–I–pyr]⁺I₃[−], respectively, can form (Figure 3). I₂ is, therefore, considered to be a soft Lewis acid, and it is logical that it should also have affinity for the soft Lewis base I[−] (*K*_{ass} 723 M^{−1}).^[9] I₃[−] is the active species in salts with cationic surfactants called iodophor(e)s in disinfectants (see Section 6), and the redox couple I[−]/I₃[−] is the electron carrier in

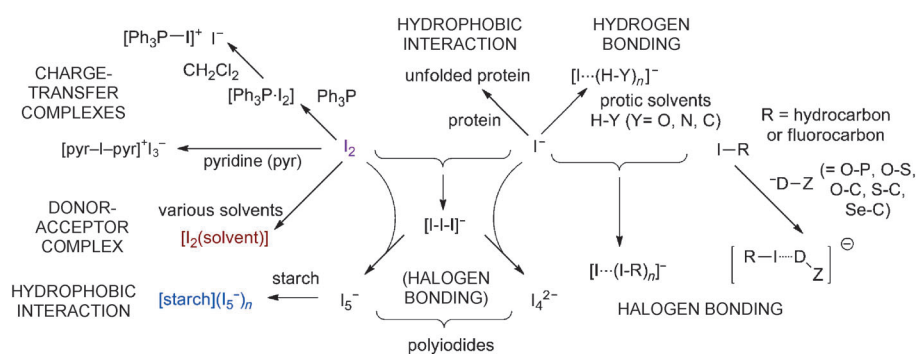


Figure 3. Overview of the supramolecular chemistry of I₂, I[−], and RI.

Grätzel-type solar cells (see Section 8).^[10] Under favorable circumstances, such as the stabilization provided to linear polyiodides by the hydrophobic interior of a starch molecule,^[11] I₃[−] can associate with more I₂ molecules to form I₅[−] ions and beyond (Figure 3); associations with I[−] to give I₄^{2−} and other polyiodide ions have also been documented^[9] (see Section 7).

In its elemental form (I₂), iodine has the lowest reduction potential of the halogens (F, Cl, Br, I), and the resulting anion (I[−]) is much larger and also much more polarizable (“soft” in the hard and soft (Lewis) acids and bases [HSAB] concept)^[12] than the other halides; it is the poorest hydrogen-bond acceptor, and its conjugate acid HI is the strongest acid in the halogen series. In coordination chemistry, its properties as both a σ and π donor place it at the extreme weak-field end of the spectrochemical series, which implies that, for example, any d-d ($t_{2g} \rightarrow e_g$ in an octahedral, $e \rightarrow t_2$ in a tetrahedral coordination geometry) transitions will be at low energy; thus iodide also promotes high-spin electron configurations of transition-metal ions. The ion is relatively hydrophobic and is at the extreme chaotropic end of the so-called Hofmeister series, which means that it strongly lowers the surface tension of the solvent and implies that it “salts in” other solutes, such as peptides, and will interact strongly with unfolded proteins.^[13] The solvation of iodide ions in various solvents has been investigated by X-ray absorption spectroscopy.^[14] Their interaction with solvent has been found to depend on the extent to which steric interactions allow hydrogen bonding to occur between the solvent heteroatoms and the iodide; thus, iodide can be hydrogen bonded by up to ten solvent molecules (in the case of water) or by only a few (for solvents with more bulky molecules, such as dimethylformamide or *tert*-butanol). The degree of dissociation of organic pyridinium iodide salts, such as 1-ethyl-4-methoxycarbonylpyridinium iodide, into ions also varies from solvent to solvent, an effect which allows the λ_{max} value of light absorption of these salts to be used as a solvent polarity index (Kosower Z value).^[15]

The iodine atom in iodohydrocarbons has Lewis acid (electron-acceptor) properties, which are even more pronounced in fluorocarbons because of the strongly electronegative fluorine substituents (which themselves are too electronegative to act as Lewis acids).^[16] This leads to a type of noncovalent interaction that has been coined the halogen bond (designated as XB: X for halogen, B for Lewis base)

because of its clear analogy to the hydrogen bond (Figure 3). Halogen bonding is now recognized as an important factor in crystal engineering,^[17] in addition to van der Waals, π - π , and hydrogen-bonding interactions. The association of $I_2 \cdot I^-$ into I_3^- in fact results in one of the strongest halogen bonds known (180 kJ mol^{-1}).^[18] The interaction of the most important iodine-containing biomolecule, the thyroid hormone thyroglobulin, with its receptors and the enzyme catalyzing its deiodination are considered to involve $C-I \cdots O=C$ ^[19] and $C-I \cdots Se-C$ (selenocysteine)^[20] halogen bonds, respectively. In the field of supramolecular receptors for the formation of iodide complexes, there are now host-guest systems in which the iodide is bound through halogen bonding to a receptor appended with monoiodoperfluorophenyl groups,^[21] in addition to those featuring $N-H \cdots I$ ^[22] and (triazole) $C-H \cdots I$ hydrogen bonds, and interactions with soft Lewis acids such as Hg in mercuracarborands.^[23]

4. Analytical Techniques for Iodine and its Compounds

In this section we will discuss the influence of various types of irradiation, including the whole range of electromagnetic radiation (spectroscopy), on iodine and its compounds. Applications for the elucidation of the structure of iodine-containing compounds, along with the application of iodine compounds for other purposes, will also be highlighted.

An overview of spectroscopic techniques and specific applications of iodine and its compounds is given in Table 1. ^{129}I is one of the few nuclei for which Mössbauer spectroscopy is applicable, by using a $27.7 \text{ keV } ^{66}\text{Zn}/^{129}\text{Te}$ source used^[24] (this and other interesting isotopes of I will be discussed in more detail in Section 14). This together with resonance Raman spectroscopy has been applied, for example, to elucidate the structure of the starch-iodine complex.^[11b] The most prominent aspect of the interaction of iodine and its compounds with X-rays is the strong contrast due to the large number of electrons resulting from its high atomic number. The application of iodine and its compounds to enhance contrast in X-ray imaging will be discussed in Section 6. More recently, the potential of X-ray absorption spectroscopy, including X-ray absorption near-edge structure (XANES), and extended X-ray absorption fine structure (EXAFS), to establish the electronic valence (XANES) and the geometric structure of iodine-containing compounds has been recognized.^[25]

The iodine-containing molecular cations and fragments generated in mass spectrometry by electron-impact ionization do not show any satellite signals, unlike those of chlorine and bromine, which have characteristic $(A/(A+2))$ isotope distributions. Since the C-I bond is relatively weak (homolytic and heterolytic bond dissociation energies of CH_3I are 234 and 887 kJ mol^{-1} , respectively), the initial molecular ion will have an electron removed from the C-I bond, thereby resulting in ready fragmentation, either to R^+ and I^- , or, because of the relatively low ionization energy of I ($1008.4 \text{ kJ mol}^{-1}$), to R^- and I^+ . In the IR absorption spectra, the C-I stretch vibrations appear at frequencies lower than those of the

other halogens. Depending on the hybridization (sp^3 or sp^2) of C, they are found at $610\text{--}485$ for aliphatic and $1061\text{--}1057 \text{ cm}^{-1}$ for aromatic compounds, where there may be overlap with other stretching and deformation transitions. The resonance Raman technique allows the vibrational frequencies associated with a UV/Vis chromophore, such as those of the polyiodides, to be specifically detected.^[11b,24] The ^{127}I nucleus with its nuclear spin of $5/2$ does not lend itself to NMR spectroscopic experiments, unlike the most abundant fluorine isotope (^{19}F , nuclear spin $1/2$), nor its coupling to other nuclei observed. In the electron paramagnetic resonance (EPR, or electron spin resonance, ESR) spectra of an I-appended nitroxide radical,^[26] and the halogen-bonded complex of a nitroxide radical with a iodofluorocarbon molecule^[27] the expected coupling to the iodine nuclear spin is not observed either, presumably because the nuclear relaxation is too rapid. However, in some cases, where radicals are centered on iodine or near iodine, characteristic sextets resulting from the hyperfine coupling structure caused by the nuclear spin of ^{127}I ($I = 5/2$) can be observed, as exemplified by the σ^* and iodine radicals formed from R-I by electron capture in solution^[28] and those formed by irradiation of KIO_4 crystals in the presence of O_2^- .^[29] More analytical techniques are discussed in other sections of this Review (especially in Sections 12 and 14).

5. Organic Synthesis

Many iodine-containing compounds—organic and inorganic—are frequently utilized as reagents in organic synthesis. Molecular iodine is mainly employed in iodinations, oxidations, and as Lewis acids.^[30] Iodine reagents with an oxidation state of $-I$ or $+I$ are sources of nucleophilic and electrophilic iodine, respectively. Polyvalent iodine compounds constitute a separate class of iodine-containing reagents, where the iodine oxidation state ranges from $+III$ to $+VII$, thus rendering it highly electrophilic.^[31] Although the first hypervalent iodine compound was already synthesized in 1886,^[32] the benefits of this class of compounds have only recently become apparent to the organic synthesis community, and has led to an upswing in a wide range of application areas.^[33]

Iodinations, oxidations, and C-C bond formation are the most important transformations mediated by iodine reagents. These highlight the versatility of these selective, nontoxic, and environmentally benign reagents (Figure 4).

The iodination of organic compounds can be achieved by nucleophilic substitution, where iodide serves as a good nucleophile for a range of electrophiles. Inorganic salts, such as NaI and KI , are often used for this purpose, although organic salts such as $(\text{Bu}_4\text{N})\text{I}$ can be more efficient due to their higher solubility in organic solvents.

Molecular iodine or KI can be used together with an oxidant for the electrophilic iodination of arenes, phenols, anilines, and heterocycles.^[30a] The iodination of alkenes and alkynes with I_2 proceeds via cyclic iodonium ions, with subsequent ring opening by a nucleophile (iodide or solvent), thereby resulting in stereospecific disubstitution. Alkanes can also be iodinated by treatment with I_2 and an oxidant. *N*-

Table 1: Overview of analytical techniques applicable to iodine chemistry.^[a]

Iodine compound	Particle	Interaction	Result	Application
iodocarbons	(70 eV) electron-impact mass spectrometer	ionization, fragmentation	$RI \rightarrow [RI]^{+\bullet} \rightarrow R^+ + I^{\bullet}$ or $R^{\bullet} + I^+$	structure elucidation
iodocarbons	radioactive source, electron capture; micro- wave klystron	hyperfine splitting of ESR signal by I nuclear spin ($I = 5/2$)	$RI + e \rightarrow [RI]^{-\bullet} \rightarrow R^- + I^{\bullet}$	electronic configuration of iodine-centered radical
¹²⁹ I	27.7 keV γ -radiation from ¹²⁹ Te	nuclear transitions: Mössbauer spectroscopy	nuclear hyperfine interac- tions, isomer shifts	characterization of iodine environment
¹²⁹ I and ¹³¹ I	–	β^- emission (0.189 or 0.970 MeV)	radio-imaging	medical imaging
iodine compounds/ complexes	X-rays at iodine K (31 keV) or L (4–5 keV) edge	X-ray-induced electron dif- fraction (EXAFS, XANES)	radial distribution func- tion	characterization of iodine environment
iodine contrast compounds I ₂ in solution or complex	X-rays UV/Vis	scattering by iodine atoms absorption	contrast in X-ray image spectrum	medical imaging characterization of com- pound/complex
colored I compounds or complexes	UV/Vis	resonance Raman, IR emission absorption	vibrational spectrum related to chromophore solvent-dependent λ_{max}	electronic/structural characterization Kosower Z value: solvent polarity index
1-ethyl-4-methoxycarbonylpyridi- nium iodide in various solvents	UV/Vis	absorption	C–I stretch at 610–485 (aliphatic) or 1061– 1057 cm ⁻¹ (aromatic)	structure elucidation
iodocarbons	infrared	absorption	blue complex in the pres- ence of both I ₂ and I ⁻	iodometry: redox titration with the starch-iodine- iodide complex as an indicator
(I ₂) _x ... (I ⁻) _n (polyiodide) in starch	visible light	absorption	mass increase correlated with number of C=C bonds	iodine value: determina- tion of the degree of unsaturation of fats
I ₂	–	addition to C=C bonds in lipids	larger clouds emission wavelength	rain making total iodine determina- tion
AgI total iodine	water inductively coupled plasma spectroscopy (ICP)	crystallization seeding emission	$Hg + 2I^- \rightarrow HgI_2 + 2e^-$ IO ₃ ⁻ to I conversion into I ₃ ⁻	I ⁻ determination IO ₃ ⁻ determination IO ₃ ⁻ determination
I ⁻	voltammetry	HgI ₂		
IO ₃ ⁻	voltammetry	reduction		
IO ₃ ⁻	visible light	absorption		

[a] Radioisotopes are discussed in Section 14.

oxidation state

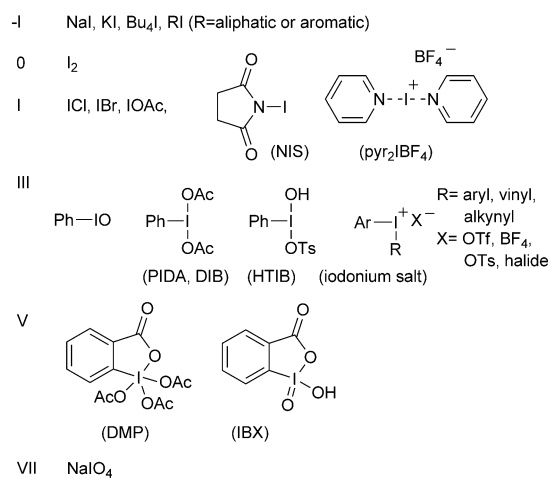
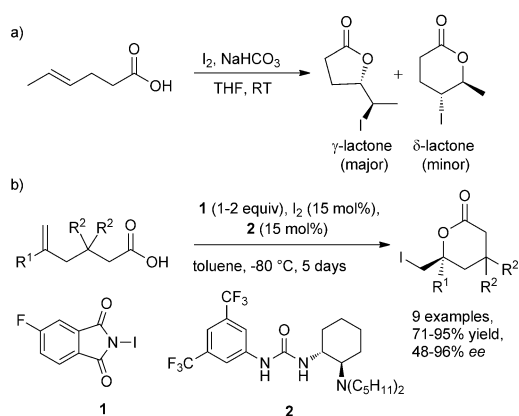


Figure 4. Common iodine reagents in organic synthesis. Tf= trifluoro-methanesulfonyl, Ts = *p*-toluenesulfonyl.

Iodosuccinimide (NIS) is used as a source of iodine in radical reactions and for various electrophilic iodinations, as exemplified by the enantioselective halocyclization of polyprenoids catalyzed by chiral phosphoramidites.^[34]

The first iodolactonization reaction was described more than a century ago.^[35] The reaction of an alkenyl-substituted carboxylic acid with molecular iodine under basic conditions proceeds by the addition of iodine to the double bond and subsequent ring closure to deliver an iodolactone in a diastereospecific fashion (Scheme 1a).^[30b,36] The reaction can be catalyzed to improve the regioselectivity,^[37] and has been employed in numerous total syntheses as a reliable way to create new stereocenters.^[36,38] The use of a chiral organo-catalyst enables highly enantioselective iodolactonization to be achieved (Scheme 1b).^[39]

Hypervalent iodine reagents are mild and powerful oxidants for a range of functional groups.^[31a,40] With the development of Dess–Martin periodinane (DMP) in 1983, an efficient, mild, selective, and metal-free oxidant for the conversion of alcohols into aldehydes or ketones was discovered.^[41] This reaction has been applied extensively in

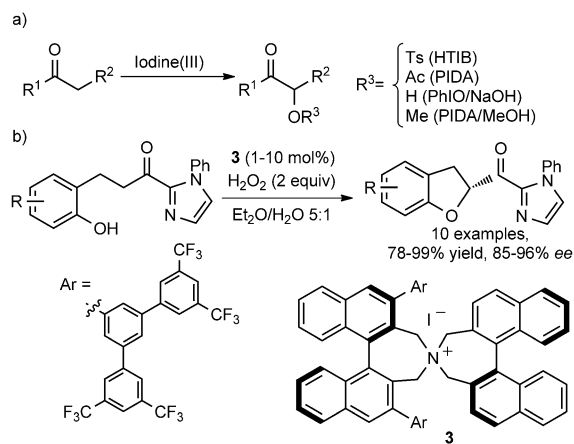


Scheme 1. Iodolactonization.

total synthesis, where more harsh oxidants are unsuitable due to the presence of other functional groups.^[42] Recent developments with 2-iodoxybenzoic acid (IBX) have broadened the scope of iodine(V)-mediated reactions beyond the oxidation of alcohols.^[42,43]

The α -oxidation of carbonyl compounds can be performed with various iodine(III) reagents, and leads to versatile intermediates for the synthesis of a variety of heterocyclic compounds and natural products (Scheme 2a).^[42c,44] A highly enantioselective oxidative cycloetherification, which was stoichiometric in hydrogen peroxide and used chiral quaternary ammonium iodide catalyst **3** as the source of asymmetric induction, was recently reported (Scheme 2b).^[45] The active oxidant was proposed to be hypiodite (IO^-) or iodite (IO_2^-), formed by oxidation of the iodide by hydrogen peroxide.

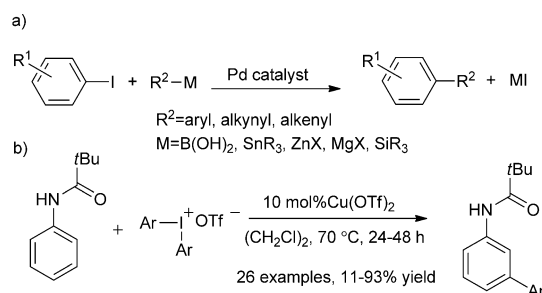
The oxidative dearomatization of phenols to cyclohexadienones is readily achieved with iodine(III) reagents or IBX,^[46] delivering intermediates that are useful in natural product synthesis.^[47] Other common transformations mediated by hypervalent iodine include oxidative aryl coupling reactions, dehydrogenation of ketones, aziridination, epoxidation, rearrangements, fragmentations, and deprotection of dithianes.^[31a] Catalytic reactions have recently been devel-

Scheme 2. α -Oxidation of carbonyl compounds.

oped, in which a stoichiometric amount of oxidant (such as *m*-chloroperbenzoic acid, *m*CPBA) and a catalytic amount of aryl iodide were used to form iodine(III) or iodine(V) in situ.^[48]

The oxidation of alcohols and aldehydes to esters, amides, and nitriles can be performed with iodine in basic solution.^[30b] These conditions are also efficient for the oxidation of thiols to disulfides, and sulfides to sulfoxides via formation of an iodosulfonium ion and subsequent nucleophilic attack by a thiol or water. The reaction is often utilized in *O*-glycosylations, where a sulfide substituent at the anomeric position is displaced.^[30b] Treatment of a methyl ketone with iodine under basic conditions results in oxidative cleavage to the corresponding carboxylic acid and iodoform (CHI_3). Sodium periodate dihydroxylates alkenes in the presence of a metal catalyst, and the obtained vicinal diols can be cleaved into two carbonyl compounds.^[49]

The formation of C–C bonds is a pivotal reaction class that has received continuous interest by the scientific community. Organometallic cross-coupling reactions have become important tools to create C–C bonds,^[50] as highlighted by the 2010 Nobel Prize in Chemistry being awarded to Heck, Negishi, and Suzuki.^[51] In the classical Ullmann reaction, biaryls are formed from aryl iodides through a copper-mediated coupling.^[52] Cross-coupling reactions now encompass a range of aryl, alkynyl, and alkenyl halides with various metalated reagents. The iodides are most reactive, with bromides and chlorides generally requiring much harsher conditions (Scheme 3a).^[53]



Scheme 3. Metal-catalyzed C–C bond formation: a) cross-coupling reaction; b) C–H activation.

Alkyl iodides are excellent alkylation reagents for a range of nucleophiles, including enolates. Hypervalent iodine reagents can also be employed for C–C bond formation, as exemplified by the arylation of enolates with diaryliodonium salts to form α -arylated carbonyl compounds.^[44a,54] Biaryls can be synthesized by metal-catalyzed C–H activation of arenes and coupling with diaryliodonium salts, as demonstrated by the *meta*-selective copper-catalyzed arylation of anilides (Scheme 3b).^[55] Another recent achievement is the metal-free cross-coupling of electron-rich arenes via diaryliodonium intermediates.^[56]

An excess of HI is classically employed in the cleavage of alkyl ethers. Iodine is often used as a catalyst in the protection of carbonyl groups as acetals or dithioacetals, as well as in the

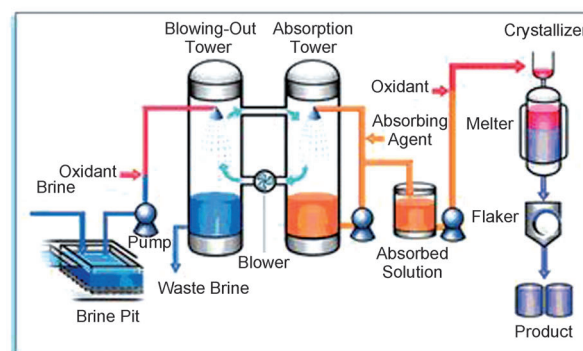
acetylation of alcohols. A trace amount of HI is formed under the reaction conditions, and this acts as the actual catalyst.^[57] Iodine is also employed in the synthesis of heterocycles, such as in the formation of pyrroles from 1,4-diketones and amines.^[30b]

6. Production and Industrial Applications

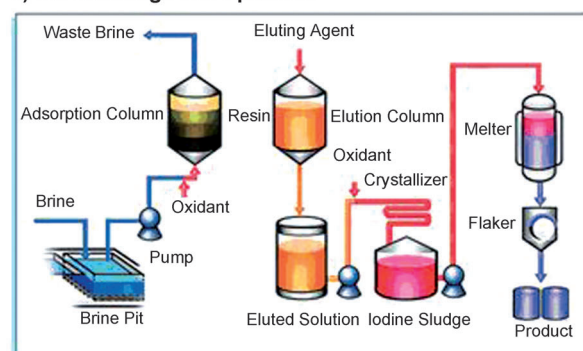
The concentration of iodine in brown seaweeds is so high that these marine algae have been used as the raw material for iodine production since the first half of the 19th century. Today, iodine production is conducted in areas where brines from natural gas and oil fields contain high iodine concentrations, as well as from Chilean caliche deposits. About $\frac{2}{3}$ of the total iodine production in the world originates from Chile and $\frac{1}{3}$ from Japan, together producing nearly 90% of the iodine globally.^[58] The brine in the Southern Kanto gas field, the industrially exploited source of iodine in Japan (and one of the largest in the world), contains approximately 100 ppm iodine. The iodine produced is supplied to the market as a flaked, granulated, or prilled solid, with a purplish black metallic luster. Two methods are employed in Japan for the production of iodine (Figure 5): 1) The “blowing out” method takes advantage of the high vapor pressure of molecular iodine and is ideal for large-scale production, including the processing of brine at high temperature; 2) the “ion-exchange resin” method uses a resin that adsorbs iodide and is suitable for both small and large production plants. In contrast, iodine production in Chile is based on the mining and leaching of nitrate ores (caliches). Caliches contain lautarite ($\text{Ca}(\text{IO}_3)_2$) and dietzeit ($\text{Ca}(\text{IO}_3)_2 \cdot 8\text{CaCrO}_4$). The solutions from the leaching of caliches carry iodine in the iodate form. Part of the iodate in solution is subsequently reduced to iodide by using sulfur dioxide obtained by the combustion of sulfur. The resulting iodide is combined with the remainder of the untreated iodate solution to generate elemental iodine. The solid iodine is then refined through a smelting process and flaked or prilled.

Iodine use is intimately involved with many aspects of our daily lives. Besides its use in iodized salt, iodine is found in a vast array of products and industrial processes. The use of iodine in solar cells is discussed in Section 8. X-ray contrast media (XRCM) are substances which enable the visualization of soft tissues in X-ray examination. The iodine atoms function as the X-ray absorbers, and their utility can be attributed to their high atomic weight (i.e. large number of electrons). Many properties are required for an ideal intravascular XRCM. These include high opacity to X-rays, high water solubility, chemical stability, low osmolality, low viscosity, and high biological safety. The non-ionic XRCMs, developed in the 1980s, including iopamidol, iohexol, and iopromide (Scheme 4), offer a significant margin of safety, have fewer side effects, and provide a high level of comfort to the patients, compared to ionic compounds. The widely used iodine tincture is an alcohol solution of iodine and potassium iodide. Iodophores are iodine complexes with surfactants that act as iodine carriers. These are water soluble and less irritating to the skin and other tissues than the tincture. Iodine

1) Blowing-out process



2) Ion-exchange resin process



3) The multiple uses of iodine

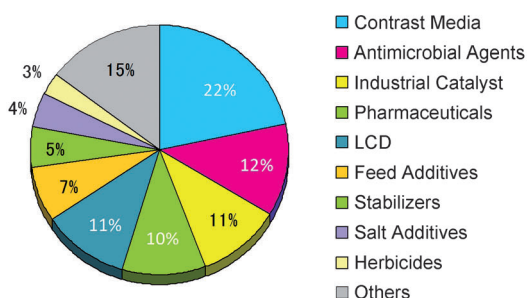
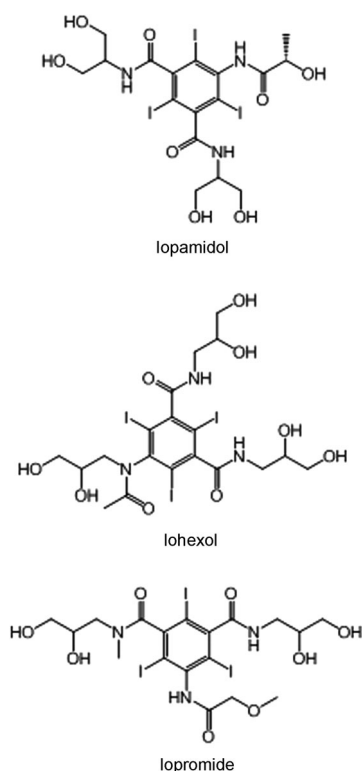


Figure 5. Two methods for the production of iodine from natural gas brine: 1) the blowing-out process, which is used in Japan, Chile, and the USA, and 2) the ion-exchange resin method, which is common in Japan. 3) An overview of the major industrial uses of iodine.

and iodophores have a wide range of antimicrobial action against Gram-positive and -negative bacteria, tubercle bacilli, fungi, and viruses. The most popular iodophore for surgical scrub and gargle is povidone iodine, which contains about 10% I_2 and releases free iodine. These forms have almost completely replaced the tincture of iodine, since they do not cause any burning sensation when applied to human tissue.

The industrial process for the production of acetic acid is currently dominated by the carbonylation of methanol. The three-step process involves iodomethane as an intermediate, and requires a catalyst, usually a metal complex, such as rhodium iodide (Monsanto process)^[8a] or iridium iodide (Cativa process).^[8b,d]

Nylon is an industrially important and useful material with multiple applications, including as an engineering resin and



Scheme 4. Non-ionic XRCMs.

fiber. Thermoplastic forms of nylon are stabilized with copper iodide. Nylon fiber producers use potassium iodide for tire and airbag cord nylon. The potassium iodide reacts in situ with cupric acetate to form cupric iodide, which acts as a heat stabilizer.

A polarizer with the function of transmitting and blocking light is a basic component of liquid-crystal displays (LCDs), along with the liquid crystal that functions as a switch for light. LCDs are used in a wide range of instruments, including computer and TV screens, navigation systems for automobiles, and instrument displays. The most common materials used in polarizing film are stretched polyvinyl alcohol films treated with absorbing iodine.

7. Materials

Elemental iodine is a solid and is formally a compound made from I_2 molecules, but it exhibits many properties expected for materials with an extended (nonmolecular) structure: it has metallic luster and semiconducting electrical properties (conductivity of about $10^{-5} \Omega^{-1} \text{cm}^{-1}$).^[59] These properties are indicative of extensive interaction between the molecular building blocks. Nevertheless, the molecular character of solid iodine is revealed by other physical properties, such as low melting point (m.p. 113.7°C), high vapor pressure (about 100 Pa at room temperature; it visibly produces violet fumes), and low bulk modulus (7.7 GPa). The dual character of iodine as a substance can be attributed to the large valence orbitals rendering a significant and uncommon overlap

between the I_2 molecules in the bulk.^[59] The conductivity can in part be attributed to a Grotthuss mechanism originating from isoheterolytical splitting of I_2 into I^- and I^+ .^[60]

As noted in Section 2, iodine reacts with most elements in the Periodic Table to form iodides. As materials, these are commonly dominated by the properties of the other element (i.e. cation), where iodine—because of its high electronegativity—acts as the negatively charged counterion or molecular entity. One such material with very versatile and widely known applications is worth mentioning though: AgI is a

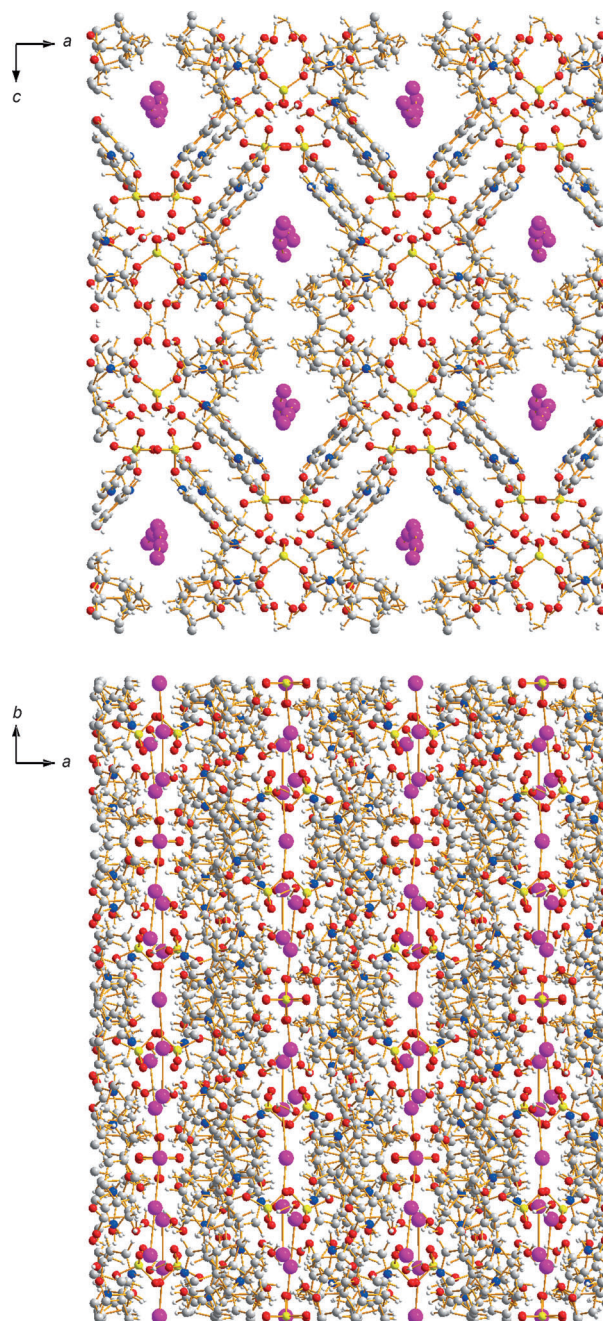


Figure 6. The structure of herapathite, in the crystallographic *b* direction (top) and *c* direction (bottom).^[43] The chains of triiodide ions running along the *b* axis are the anisotropic origin of its optical properties. Gray C, red O, yellow S, pink I, blue N, white H.

superionic (silver ion) conductor in its α modification, it can be used in (conventional) photography, and as a rain initiator. Exceptions are iodine-rich compounds, so-called polyiodides.^[61] Such materials have been used extensively in chemistry and often without exact knowledge of the structure and/or origin of their properties (particularly optical properties). Two such examples are the strong violet, starch-based indicator used in iodometric titrations,^[11b] and herapathite, which was used as a light polarizer for over 150 years before its structure was very recently elucidated. Its function was attributed to the formation of chains of triiodide ions to give a low-dimensional structure and thereby anisotropic optical behavior.^[62] The crystal structure of the optically active herapathite material is shown in Figure 6. The formation of low-dimensional structures in iodine-rich compounds is archetypical.

Polyiodides are normally formulated as $[mI^- \cdot nI_2]$, where the smallest polyiodide entity is with $m = 1$ and $n = 1$, that is, I_3^- , the triiodide ion. Triiodides normally form isolated ions in their structures, or alternatively interconnected chains, such as in herapathite. As n increases, the structural chemistry becomes more complex. At $m = 1$ and $n = 2$, which corresponds stoichiometrically to pentaiodides, several alternatives already exist, sometimes together in the same structure: either isolated linear or V-shaped ions, or interconnected zigzag chains. Chain-linked, low-dimensional structures are common and, from a coordination chemistry point of view, the structures can be divided into three fundamental building blocks: I^- and I_3^- ions interspaced, or solvated, by neutral I_2 molecules. Since chainlike structures are typically obtained, anisotropic physical properties are common. The most iodine-rich compound known to date is I_{29}^{3-} , which can be regarded as being composed of $[(I_5^-) \cdot (I_{12}^{2-})_{1/2} \cdot 3I_2]$.^[63] As the iodine content increases, the thermal stability also decreases because of evaporation of I_2 . Cationic polyiodides, such as I_2^+ , I_3^+ , I_4^{2+} , and I_5^+ polyiodonium ions, can also be isolated in Lewis acidic media.^[61a]

A special class of compounds, highly related to polyiodides in terms of structure and composition, are the interhalogen compounds.^[64] In this case, iodine reacts with the other halogens to form mixed compounds, where the most electronegative elements (thus, normally not iodine) typically take the terminal positions in the molecular entities. Since interhalogen compounds, just as polyiodides, are hypervalent, they take on rare molecular structures, such as the T-shaped IF_3 , pyramidal IF_5 , or pentagonal bipyramidal IF_7 , in which the iodine atom assumes the role of a coordination center—almost like a metal cation. Numerous inter-polyhalonium cations with interesting molecular structures are also known.

8. Solar Cells Based on the Conductance of Polyiodides

The type of solar cells associated with electrolytes containing a mixture of iodine and iodide, that is, the dye-sensitized titanium oxide (TiO_2) solar cell (DSC), was significantly improved by Grätzel, now recognized worldwide as one of the most promising types of solar cells for the profitable and environmentally friendly production of electricity.^[65] The light-to-energy conversion efficiency in such solar cells is higher than that of thin-layer silicon solar cells.^[66] Figure 7 shows the schematic structure of efficient DSCs with anatase nanocrystalline TiO_2 (nc- TiO_2) as the electron-accepting and electron-transporting layer (crystal size 15–30 nm, thickness 10–15 μm), a panchromatic ($\lambda \approx 940$ nm) ruthenium dye (N749) derived from carboxylated terpyridyl and tris(thiocyanato), and an I^-/I_3^- electrolyte as the source of polyiodides for charge transport and redox reactions at the electrode interfaces.

A typical redox-active electrolyte contains butylmethylimidazolium iodide ([RMIm]I; R = butyl, M = methyl; 0.6 M) as a fluid and nonvolatile iodide (an ionic liquid), iodine (0.1–0.15 M), *tert*-butylpyridine (TBP; 0.05 M) or *N*-methylbenzimidazole (NMBI; 0.1 M), and guanidium thiocyanate (GSCN; 0.1 M) in an acetonitrile/valeronitrile (75:25) solvent mixture. The addition of TBP or NMBI as well as GSCN contributes to the unidirectional electron flow in the devices by suppressing electron recombination or leakage at the interfaces of the mesoporous dyed nc- TiO_2 layers. The high conversion efficiency (ca. 12%) originates from $J_{sc} \approx 21$ mA cm⁻², $V_{oc} \approx 720$ mV, and a fill factor of about 0.75 (J_{sc} = short-circuit current density, V_{oc} = open-circuit voltage, fill factor = $P_{max}/(J_{sc} V_{oc})$; P_{max} = the product of the photocurrent and photovoltage at the voltage where the power output of the cell is maximal).^[67]

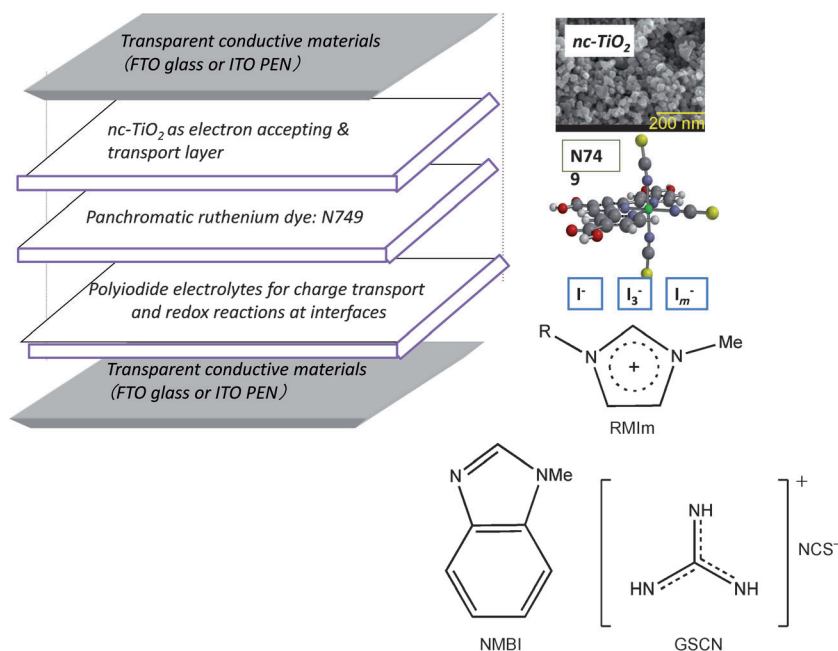


Figure 7. Schematic structure of a dye-sensitized solar cell (DSC). TFO = fluorinated tin oxide, ITO = indium-doped tin oxide, PEN = polyethylene naphthalate.

The excellent conductance of the electrolytes, as liquid *p*-type semiconductors, was nicely analyzed by using the ionic liquid-crystal (ILC) electrolyte [RMIm]I, R = dodecyl or C₁₂, as well as ([C₁MIm])/I₂. The ILC has a liquid-crystal smectic A (SA) phase at 21–46 °C.^[68] The ILC gives a higher diffusion coefficient than the related but isotropic ionic liquid electrolyte [C₁₁MIm]/I₂ (Figure 8). The triiodide (I₃⁻) and the polyiodide species (I_{*m*}⁻) can be identified at Raman shifts of 110 cm⁻¹ and 150 cm⁻¹, respectively (Figure 9a), and the

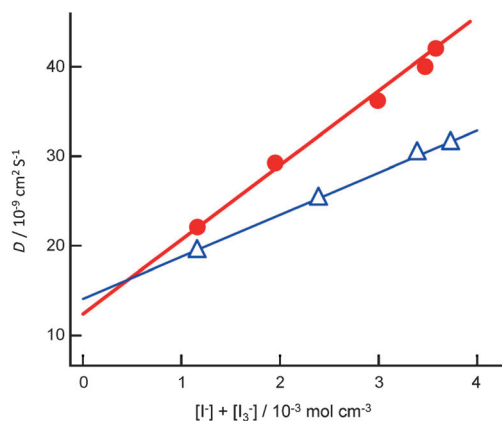


Figure 8. Diffusion coefficients (*D*) of I₃⁻ as a function of concentration ([I⁻] + [I₃⁻]) for anisotropic [C₁₂MIm]/I₂ (●) and isotropic [C₁₁MIm]/I₂ (△).

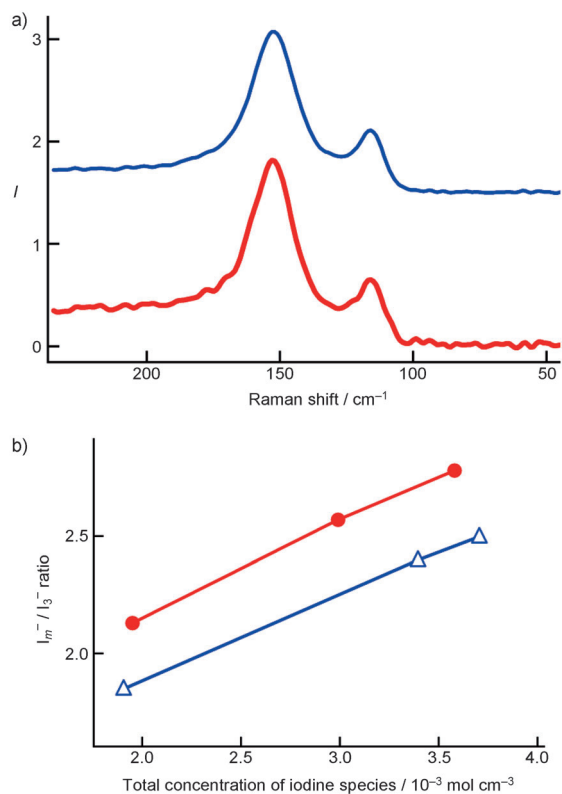


Figure 9. a) Raman spectra for [C₁₂MIm]/I₂ (red) and [C₁₁MIm]/I₂ (blue) at 40 °C. b) I_{*m*}⁻/I₃⁻ ratio as a function of total concentration of iodide species for [C₁₂MIm]/I₂ (●) and [C₁₁MIm]/I₂ (△).

latter increases with increasing polyiodide concentration (I_{*m*}⁻). Furthermore, the ratio of I_{*m*}⁻/I₃⁻ in the ILC electrolyte was found to be larger than that of the [C₁₁MIm]/I₂ electrolyte (Figure 9b), which implies that the amount of I_{*m*}⁻ increases as a result of the concentration effect at the SA layer.

Measurements of the anisotropic ion conduction revealed that the conductivities of the ILC change dramatically at the liquid-crystal SA phase, and increase along the direction parallel to the SA layer plane [σ_{ij} (filled circle)], and become higher than along the direction perpendicular to the plane [$\sigma_{i\infty}$ (open triangle)] (Figure 10). Accordingly, the formation of the two-dimensional conductive polyiodide layers at the SA phase plays an important role in the enhancement of the exchange-reaction-based diffusion, as depicted in Figure 10b.

As for the conductance of polyiodide systems, it is worth mentioning that some organic and inorganic polyiodides are conductive as solids (10⁻⁵–10⁻² Ω⁻¹ cm⁻¹) and the influence of counteranions—such as the radical anion of tetracyanoquinodimethane (TCNQ^{•-}) and the tetramethylammonium

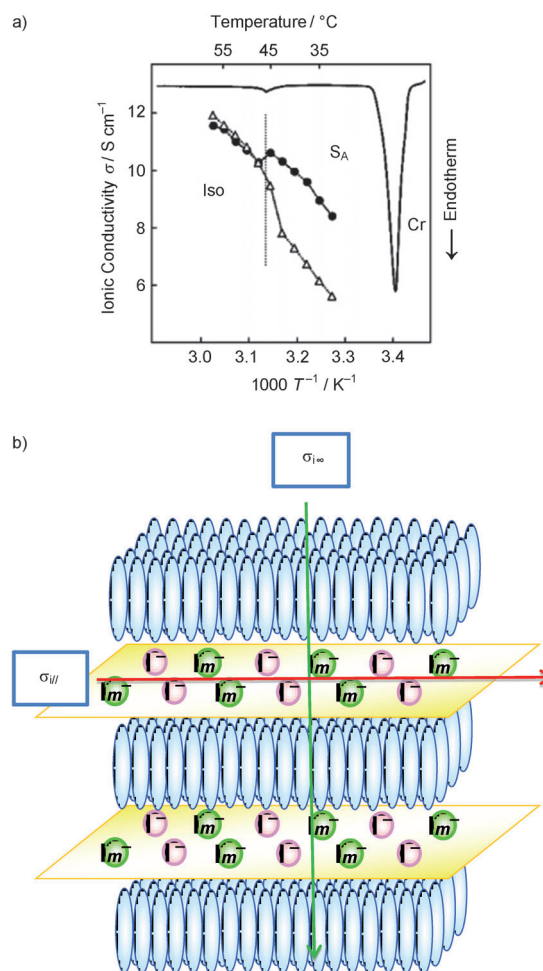


Figure 10. a) Differential scanning calorimetric traces and ionic conductivities for the sample of [C₁₂MIm]/I₂ along the direction parallel (σ_{ij} , red circle) and perpendicular ($\sigma_{i\infty}$, green triangle) to the SA layer plane of the σ_i homeotropically aligned ionic liquid crystal (Iso: isotropic; SA: smectic A; cr: crystalline). b) Schematic representation of the SA layer of [C₁₂MIm]/I₂.

cation $[(\text{CH}_3)_4\text{N}^+]$ —is of subordinate importance for the observed conductivity.^[69] The same is true for the conductance of iodine-doped polyolefin complexes. After the discovery of conductive iodinated polyacetylene films, π conjugation of the polymer backbone was thought to be a prerequisite for the formation of a conductive charge-transfer complex upon doping with iodine. However, the conductivity is primarily due to polyiodides coupled with iodine-oxidized polyolefins.^[70] In other words, a conjugated backbone of the polyolefins is not a prerequisite, and polyiodide species play a decisive role for the conductivity of the iodine-doped polymers.

Mikawa and co-workers^[71] reported that tetramethylammonium polyiodide $[(\text{CH}_3)_4\text{N}^+]\text{I}_m^-$ (I_m^- , $m=3, 5, 9$) crystals show *p*-type semiconducting properties, and that the electrical resistivity ranges from 10^{-7} to $10^{-10} \Omega^{-1} \text{cm}^{-1}$ at room temperature. Furthermore, the activation energy (1.3–2.3 eV) for electronic conduction decreases as the number of iodine atoms in the polyiodide ions increases. The authors also observed that I_5^- had a dramatically enhanced conductivity compared to I_3^- , as well as an anisotropy of its conductance in the direction of the iodine atom nets. They discussed the conductance in view of the reported X-ray crystallography data, and pointed out that I_3^- species exist as linear, discrete entities (4.03 Å in CsI_3), and that I_5^- in $[(\text{CH}_3)_4\text{N}^+]\text{I}_5^-$ is packed in a dense layered structure of approximately square nets containing five iodine atoms. In the most conductive enneaiodide $[(\text{CH}_3)_4\text{N}^+]\text{I}_9^-$, $5/9$ of the iodine atoms produce an I_5^- layer of rather densely packed polyiodide ions, and the remaining iodine atoms exist in the form of diatomic iodine molecules, which act as connecting elements between the I_5^- layers. A recent X-ray crystallography analysis revealed that the most iodine-rich polyiodides are also composed of V-shaped I_5^- units connected into linear chains.^[63]

The thermodynamic and structural properties, as well as the energetic and electronic structures of isolated polyiodide ions (I_m^- , $m=1, 3, 5, 7, 9$) were analyzed by using Spartan'08 at the B3LYP/6-31G* level of the density functional theory (DFT). Their physical properties are shown in Table 2. The absorption spectrum of the polyiodide electrolyte containing 1M iodine and iodide usually emerges at $\lambda=490\text{--}360 \text{ nm}$.^[72] It should be noted that iodine becomes very soluble in iodide-based ionic liquids, such as 1-alkyl-3-methylimidazolium iodides ($[\text{RMI}]\text{I}$, R=pentyl, hexyl, and nonyl). Interestingly, the viscous ionic liquids become more fluid and the viscosity decreases as the amount of added iodine increases. At the same time, the conductivity increases, as expected.^[72]

Table 2: Frontier molecular orbital energy, UV/Vis absorption, dipole moment, and thermodynamic change obtained at the DFT B3LYP/6-31G* level of theory for a series of polyiodide ions.

Polyiodide	E_{LUMO} [eV]	E_{HOMO} [eV]	E_{gap} [eV], [nm]	λ_{max} (I_{rel}) [nm]	Dipole moment [Debye]	E [kcal mol ⁻¹]	E per I atom [kcal mol ⁻¹]
I^-	17.09	-0.03	17.12, (-)	-	0	-7198.93	7198.93
I_3^-	0.69	-2.46	3.15, (393)	433 (0.00013)	0.9	-21 537.80	7179.26
I_5^-	-0.49	-3.43	2.94, (421)	533 (0.013)	0	-35 855.19	7171.04
I_7^-	-1.21	-4.02	2.81 (441)	535 (0.028)	0	-50 166.58	7166.65
I_7^- (2D)	-1.43	-3.96	2.53, (490)	580 (0.030)	2.43	-50 164.49	7166.35
I_9^- (2D)	-2.36	-4.20	1.84, (673)	651 (0.175)	0.15	-64 467.24	7163.03
I_9^- (3D)	-1.59	-4.39	2.80, (443)	568 (0.020)	0	-64 472.01	7163.56
I_7^-		I_7^- (2D)		I_9^- (2D)			I_9^- (3D)

These results, together with the structural information regarding densely packed I_5^- units in the crystalline state, suggest that I_3^- and I_5^- are present in fluid polyiodide electrolytes, and contribute to the effective electron transport in DSC devices.

Figure 11 shows a molecular orbital model of electron transport between the anode of nc-TiO₂ and the cathode in DSCs, taking into consideration conductance to the perpendicular I_5^- net. The dye molecule N749 was calculated to have a HOMO level of -2.45 eV (at the same level of DFT theory as noted above). When the dye has been photoexcited and the electron in the LUMO injected into the nc-TiO₂, the HOMO level of I^- is high enough to inject an electron into dye N749. The LUMO levels of I_3^- and I_5^- indicate that they are good

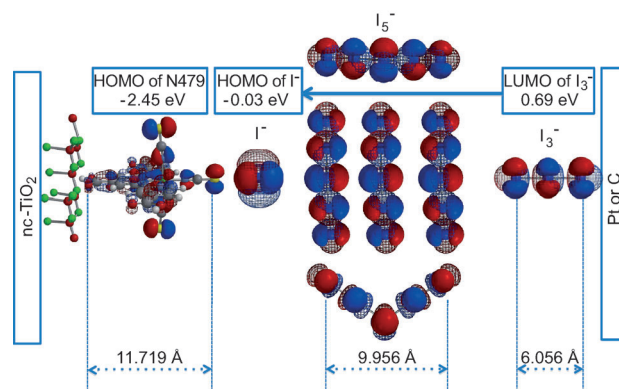


Figure 11. Electron-transport scheme in DSCs based on a collision and exchange mechanism in polyiodide electrolytes.

electron acceptors upon reduction at the counter electrodes. The average distance of ion species in electrolytes is known to be around 6.5 Å at a concentration of 1M.^[73] The distance does not seem to be too great for the large I_5^- to undergo effective collision in the electrolytes. The exchange reaction mechanism through the polar V-shaped I_5^- could be a source of conductance of iodine/iodide electrolytes and of the excellent performance of DSCs.

9. Medicine and Physiology

Iodine is an essential component of hormones produced by the thyroid gland. Thyroid hormones, and therefore iodine, are essential for mammalian life. Iodine is ingested in several chemical forms. Iodide is rapidly and nearly completely absorbed in the stomach and duodenum. In healthy adults, the absorption of iodide is >90%.^[74] The distribution space of absorbed iodine is nearly equal to the extracellular fluid volume. Iodine is cleared from the circulation mainly by the thyroid and kidney, and while renal iodine clearance is fairly constant, thyroid clearance varies with iodine intake. In conditions of adequate iodine supply, ≤10% of absorbed iodine is taken up by the thyroid. When there is a chronic iodine deficiency, this fraction can exceed 80%. Iodine in the blood is turned over rapidly; under normal circumstances, plasma iodine has a half-life of about 10 h, but this is shortened if the thyroid is overactive, as in iodine deficiency or hyperthyroidism.

The body of a healthy adult contains up to 20 mg iodine, of which 70–80% is in the thyroid. In iodine-sufficient areas, the adult thyroid traps 60–80 µg of the iodine per day to balance the losses and maintain synthesis of the thyroid hormone. A transmembrane protein in the basolateral membrane, the sodium iodide symporter (NIS), transfers iodide into the thyroid at a concentration gradient 20 to 50 times that of plasma. The NIS concentrates iodine by an active transport process that couples the energy released by the inward translocation of sodium down its electrochemical gradient to the simultaneous inward translocation of iodine against its electrochemical gradient. At the apical surface of the thyrocyte, the protein transporter pendrin moves iodide into the follicular lumen, where the enzymes thyroperoxidase (TPO) and hydrogen peroxide oxidize iodide and attach it to tyrosyl residues on thyroglobulin to produce monoiodotyrosine (MIT) and diiodotyrosine (DIT), the precursors of thyroid hormones. TPO then catalyzes the coupling of the phenyl groups of the iodotyrosines through a diether bridge to form the thyroid hormones. The linkage of two DIT molecules produces thyroxine (T4), and linkage of a MIT and DIT produces triiodothyronine (T3), the active form of the hormone. T3 is structurally identical to T4 but has one less iodine atom (at the 5'-position on the outer ring; Figure 12). The first chemical model for the inner-ring deiodination of T4 and T3 by iodothyronine deiodinase ID-3 has recently been demonstrated.^[75] Iodine comprises 65 and 59% of the molecular weight of T4 and T3, respectively. In the blood stream, thyroid hormones are bound noncovalently to carrier proteins, mainly thyroxine-binding globulin. In target tissues,

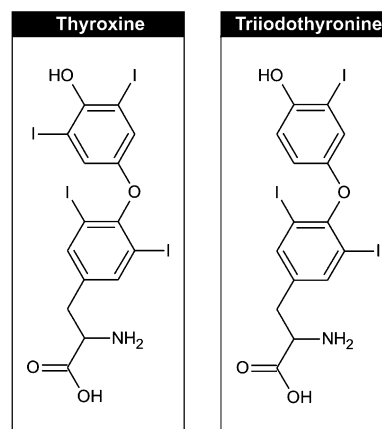


Figure 12. Iodine is an essential component of the thyroid hormones triiodotyrosine (T3) and thyroxine (T4).

interactions between the thyroid hormone and receptor stimulate several pathways. Both T4 and T3 are degraded through a complex series of pathways, and their conversion is relatively slow: the half-life of T4 is about 5 days, and 1.5 to 3 days for T3. More than 90% of ingested iodine is ultimately excreted in the urine, with only a small amount appearing in the feces. Thyroid hormones regulate a variety of physiologic processes, including reproductive function, growth, and development.^[76] The thyroid hormones increase the energy metabolism in most tissues, and raises the basal metabolic rate. The principal regulator of thyroid hormone metabolism is the thyroid-stimulating hormone (TSH), a protein hormone (molecular weight ca. 28000) secreted by the pituitary. TSH secretion is controlled through negative feedback by the level of circulating thyroid hormone. Since the primary stimulus to TSH secretion is circulating thyroid hormone, an elevated TSH concentration in serum generally indicates primary hypothyroidism, while a low concentration indicates primary hyperthyroidism.

Deficiency. Iodine deficiency has multiple adverse effects on the growth and development of animals and humans. These are collectively termed the iodine deficiency disorders (IDD; Table 3), and are one of the most important and common human diseases.^[77] They result from inadequate thyroid hormone production because of a lack of sufficient iodine. Thyroid enlargement (goiter) is the classic sign of iodine deficiency. It is a physiological adaptation to chronic iodine deficiency. As iodine intake falls, secretion of TSH increases in an effort to maximize the uptake of available iodine, and TSH stimulates thyroid hypertrophy and hyperplasia. Although goiter is the most visible effect of iodine deficiency, the most serious adverse effect is damage to reproduction. Severe iodine deficiency during pregnancy is associated with a greater incidence of stillbirths, miscarriages, and congenital abnormalities. Iodine prophylaxis with iodized oil in pregnant women in areas of severe deficiency reduces fetal and perinatal mortality.^[78] The most severe form of neurological damage from fetal hypothyroidism is termed cretinism. It is characterized by gross mental retardation along with various degrees of short stature, deaf mutism, and spasticity.^[79] Up to 10% of a population with severe iodine

Table 3: The iodine deficiency disorders, ordered by age group.^[77]

Age groups	Health consequences of iodine deficiency
all ages	goiter increased susceptibility of the thyroid gland to nuclear radiation
fetus	abortion stillbirth congenital anomalies perinatal mortality
neonate	infant mortality
–	endemic cretinism
child and adolescent	impaired mental function delayed physical development
adults	impaired mental function reduced work productivity toxic nodular goiter; iodine-induced hyperthyroidism hypothyroidism in moderate-to-severe iodine deficiency

deficiency may be cretinous. Although new cases of cretinism are now rare, even mild deficiency can impair cognitive development. A meta analysis of 18 studies concluded that moderate-to-severe iodine deficiency reduces mean IQ scores by 13.5 points.^[80] Iodine deficiency is thus considered one of the most common causes of preventable mental retardation worldwide. The World Health Organization (WHO) recently estimated the worldwide prevalence of iodine deficiency. Just over 2 billion individuals have inadequate iodine nutrition, of whom 266 million are school-aged children.^[81] The WHO has also recommended an iodine intake for adults of 150 µg per day.^[77]

There are two methods commonly used to correct iodine deficiency in a population: iodized oil and iodized salt. In nearly all regions affected by iodine deficiency, the most effective way to control iodine deficiency is through salt iodization.^[77] Iodine can be added to salt in the form of potassium iodide (KI) or potassium iodate (KIO₃). More than 120 countries have implemented salt iodization programs and approximately 70% of people worldwide had access to iodized salt in 2006, compared to < 10% in 1990.^[82] Other options for the correction of iodine deficiency should also be considered, such as iodized oil or KI supplements.^[77]

Excess. Acute iodine poisoning caused by the ingestion of many grams of iodine causes gastrointestinal irritation, abdominal pain, nausea, vomiting, and diarrhea, as well as cardiovascular symptoms, coma, and cyanosis. Most people are remarkably tolerant to high dietary intakes of iodine. The US Food and Nutrition Board of the National Academy of Sciences has set a Tolerable Upper Intake Level (UL) for iodine at 1100 µg per day for adults.^[74]

Radiation safety (see Section 14). Radioactive ¹³¹I was one of the major isotopes of concern for human health in the fallout from the Chernobyl accident, and caused several thousand cases of thyroid cancer. Consequently, the role of

iodine radioisotopes has been studied extensively since then (for a review, see for example Ref. [83]).

10. Iodine Biochemistry

It is not entirely surprising that iodine was discovered as a novel element in the ashes of *Laminaria* and related brown algae (Figure 1), since they are the strongest accumulators of iodine among all living systems.^[84] Even though iodine had been discovered in seaweed ashes, it was not until the late 19th century that algal iodine metabolism received any research interest. Exemplary for this period are the studies of Eschle,^[85] who investigated the iodine content of *Fucus vesiculosus* and *Laminaria digitata*. Golenkin reported as early as 1894 the release of free iodine from the red alga *Bonnemaisonia asparagoides*—detected by a blue stain of starch on paper.^[86] Several decades passed until this was more widely accepted by the community, in particular as a consequence of the studies of Sauvageau^[87] on red algae, and of Kylin^[88] and Dangeard^[89] in the 1920s. The latter two researchers, clearly working in competition, were the first to report the emission of molecular iodine (I₂) from kelp (*L. digitata*) surfaces which was termed “iodovolatilization”. The rise of nuclear physics and the availability of radioisotopes enabled studies of the uptake mechanism of iodine in brown algae, notably those by Tong and Chaikoff on the Pacific kelp *Nereocystis luetkeana*,^[90] by Bailey and Kelly on *Ascophyllum nodosum*,^[91] and by Shaw on *Laminaria*.^[92]

More recently, it became clear that vanadium haloperoxidases, an intact cell wall, and low levels of hydrogen peroxide are required for sustained iodine uptake—protoplasts (i.e. algal cells, from which the cell wall has been enzymatically removed) do not take up iodine.^[84b] Only the macroscopic *Laminaria* sporophytes take up significant levels of iodine—the haploid, filamentous gametophytes do not. The former have high levels of haloperoxidases, the latter do not. However, iodine uptake can be induced in gametophytes by addition of exogenous H₂O₂ and haloperoxidase. Iodoperoxidases were subsequently purified from *Laminaria*, a novel subclass of vanadium haloperoxidases,^[93] which may explain the selectivity for iodide uptake in *Laminaria*. Iodine is accumulated in the apoplast of cortical *Laminaria* tissues.^[94]

The biological significance of iodine accumulation in kelps was elucidated recently. X-ray absorption spectroscopy showed that the accumulated form is iodide, which is contained in a largely organic (rather than hydrated) environment. It serves as a simple inorganic antioxidant, protecting the apoplast (cell wall space) of the cortical cell layers,^[95] analogous to the hypothesis proposed by Venturi and Venturi^[96] for animal systems. Upon oxidative stress, such as an oxidative burst,^[97] a transition to a more hydrated form occurs. Concomitantly, a strong efflux of accumulated iodide occurs. This constitutes the description of the first inorganic and of the chemically simplest antioxidant known from a living system.^[95] Indeed, the reaction of iodide with the major reactive oxygen species is both thermodynamically and kinetically favorable. With the involvement of vanadium haloperoxidase and in the absence of organic cosubstrates,

iodide effectively degrades H_2O_2 (halide-assisted disproportionation of hydrogen peroxide). Furthermore, the millimolar levels of iodide on the *Laminaria* surface exposed at low tide effectively scavenge atmospheric ozone, leading to the release of I_2 at rates up to about five orders of magnitude higher than the combined iodocarbon emissions. These studies^[95,98] unambiguously clarify the biochemical origin of particle-forming iodine oxides: Molecular iodine is photolyzed and further oxidized by ozone in the marine boundary layer, thereby producing hygroscopic iodine oxides. The latter form ultrafine particles, which lead to aerosol formation—thus establishing a unique link between a biological antioxidant and climatic processes. A recent study in Ireland^[99] supports the hypothesis that human iodine intake in coastal regions is dependent on seaweed abundance rather than proximity to the sea.

Nevertheless, major open questions remain regarding the accumulation of iodide in kelp. So far, it is not clear how iodide is fixed in the apoplast, nor how its mobilization from this storage occurs during oxidative stress—both aspects arguably have some bioengineering potential. The recent completion of the first brown algal genome^[100] should help to provide new insight in this regard. However, the efflux of iodide during oxidative stress may be rather widespread in seaweeds: Besides *Laminaria*, this mechanism has been observed in both brown and red algae.^[101] It should also be highlighted that the biosynthetic pathways of iodinated halocarbons in marine algae^[102] remain largely unknown to date.

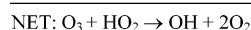
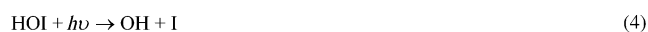
While algae have received most interest from biochemists, in addition to iodine accumulation in the thyroid, the role of microbes in global iodine cycling remains underexplored. Iodide oxidation linked to the formation of free iodine was first observed with a marine bacterium, *Pseudomonas iodooxidans*, in a marine aquarium, where the process was blamed for fish fatalities.^[103] Iodide-oxidizing bacteria occur in low abundance in seawater (from which they can be enriched by adding higher iodide concentrations) and in much higher abundance in iodide-rich brines accompanying natural gas deposits.^[104] Bacterial nitrate reductase activity has been implicated in the reduction of iodate in seawater.^[105] More recently, an iodate-reducing, anaerobic *Pseudomonas* sp. was isolated from marine sediment.^[106] A wide range of bacteria in terrestrial and marine environments are capable of methylating iodide,^[107] and microbes have been implicated in iodine sorption in soils.^[108] Recently, iodine-accumulating bacteria were isolated from marine sediment, with an uptake mechanism reminiscent of that described for brown algae.^[109]

Relatively little is known about organic iodine metabolites and natural products other than the thyroid hormones. A recent review^[110] mentions just over 110 known iodine-containing natural products, most of which originate from marine organisms.

11. Atmospheric Chemistry

The presence of iodine in the marine atmosphere was established in the early 1970s, with evidence of a primary

gaseous source from the ocean that is ultimately scavenged from the gas phase by aerosol particles.^[111] A few years later, model calculations^[112] indicated that the abundance of reactive iodine oxide (IO) radicals in the lower atmosphere (troposphere) could be sufficient to increase loss rates of tropospheric ozone (a greenhouse gas, and at elevated concentrations a threat to human health and plant growth) and affect key atmospheric oxidation processes. IO was suggested to arise predominantly from photodissociation of methyl iodide (CH_3I) to I atoms followed by rapid reaction with O_3 [Eq. (2)], thereby leading to catalytic cycles for O_3 loss.



Despite significant additions and revisions to the atmospheric mechanisms and kinetics of iodine photochemistry, and indeed to the strength and nature of iodine source gases, the major features of these early predictions have been borne out.

Observational evidence for the presence of IO was first reported at the coastal site of Mace Head, Ireland,^[113] and since then numerous studies have indicated that IO is ubiquitous in the air above kelp-rich coastlines, with reported levels of up to about 50 parts per trillion by volume (pptv).^[114] However, it has become clear that such coastal regions offer a unique iodine-rich environment arising from direct emissions of very reactive molecular iodine (I_2) from seaweed,^[98,115] which in the atmosphere breaks down rapidly to I atoms, thus producing IO [Eq. (2)]. It has long been established that seaweeds, particularly kelps, emit volatile organic iodine compounds (VOICs),^[102,116] however, it now appears that the inorganic iodide efflux leading to I_2 formation after an oxidative burst is some three orders of magnitude higher than organic iodine emissions.^[95]

Volatilization of I_2 from kelps exposed to air appear to explain the observations^[117a,b] of coastal “bursts” of iodine-containing ultrafine aerosol particles at low tide during the day. Iodine oxide particles (IOPs) are thought to arise through recombination reactions of IO and OIO (formed from the IO self-reaction and IO + BrO cross-reactions) to form higher oxides followed by condensation of further species, such as sulfuric acid.^[118] Evidence for the ability of these particles formed from iodine to grow to the point of becoming cloud condensation nuclei (CCN), and thus affect cloud brightness and hence climate, has been recently demonstrated by McFiggans et al.^[119]

Although strong links between iodine, new particles, and particle growth have now been established, the chemistry of the particle-forming higher oxides of iodine is poorly understood;^[120] these reactions also impinge on the impact of iodine on gas-phase atmospheric chemistry. For comprehensive reviews on experimental data for reactions of iodine, the reader is referred to the 2003 special issue of *Chemical Reviews* on atmospheric chemistry,^[121,122a] and a second review on iodine in *Chemical Reviews*,^[122b]

Recent measurements of IO at the tropical open Atlantic Cape Verde Observatory (located on a volcanic island with a negligible seaweed population) suggest a potential global role of iodine chemistry.^[123] The presence of reactive iodine species can activate the release of bromine and chlorine through heterogeneous reactions on the sea-salt aerosol,^[124] and the combined presence of halogens in the marine environment acts synergistically to catalyze O₃ destruction, for example, through the cross-reaction of IO with bromine oxide (BrO).^[125] These reactions occur in addition to Equations (2)–(4) and other O₃-depleting cycles. At Cape Verde, the result is an approximately 40% increase in the rates of photochemical O₃ destruction (compared to a hypothetical situation without halogens), with iodine responsible for about 2/3 of the halogen-related loss.^[123] The observed depletion of ozone in this region cannot be explained without the presence of halogen compounds.

The presence of iodine can also result in increased OH levels [e.g. through Equations (3) and (4)]. Models predict an increase in surface [OH] of about 10% in the low-NO_x open-ocean environment,^[123b,126] which in turn reduces the lifetime of methane and hence has implications for the climate. The precise effects of such chemistry requires knowledge of the vertical profile of iodine within the lower troposphere (see, for example, Refs. [126,127]). It remains an open question as to whether there is sufficient iodine over the open ocean to form IOPs which survive long enough to condense and have an impact on marine CCNs.

A surprising recent discovery is that significant quantities of IO are present in polar regions, even those remote from ocean sources, as observed from ground-based observations of several pptv of IO in both the Arctic and Antarctic,^[128] as well as from satellite observations of atmospheric columns of IO over Antarctica.^[129] Complete destruction of O₃ by bromine chemistry during so called “ozone-depletion events” (ODEs) is a regular feature of the polar lower troposphere in spring.^[130] As a consequence of the strong chemical coupling with BrO, and the high abundance of bromine in the polar environment,^[131] even a few pptv of IO can amplify O₃ destruction.^[128c,132] The presence of iodine is also suggested to enhance the oxidation of gaseous elemental mercury (Hg⁰) to reactive gaseous mercury (Hg^{II}),^[128d,133] which subsequently deposits on the snow, potentially leading to bioaccumulation of soluble and toxic forms of mercury.

Although it is considered that molecular iodine from seaweeds is the main source of coastal iodine, the sources of both open-ocean and polar iodine are very poorly understood. It is now known that CH₃I is not the only open-ocean source; recent data suggest that more-reactive VOICs such as CH₂ICl and CH₂I₂ play a significant role, perhaps contributing as much iodine globally as CH₃I,^[134] and a greater source of I atoms for the atmospheric boundary layer.^[127] Despite this, measurements of VOIC in the region of Cape Verde^[127] could not be reconciled with the observations of IO,^[123b] even given the uncertainties in the kinetic parameters, and suggest a significant additional source of iodine. Several mechanisms for the release of small halogen molecules from the ocean surface following atmospheric deposition of O₃ on the sea surface have been proposed, including the reaction with

seawater I⁻ to evolve I₂^[135] or VOICs^[136] or by oxidation of halogen anions to their radical forms by marine photosensitizers such as aromatic ketones.^[137] The reaction of O₃ with I⁻ at the air–water interface is also reported to produce IO in addition to I₂, albeit at much lower levels.^[138] As yet, there have been no reported unambiguous measurements of I₂ in seawater or marine air away from coastal regions to confirm whether these proposed mechanisms operate efficiently in the marine environment.

Recent measurements on polar iodine sources at the Antarctic suggest that very high IO concentrations are present in interstitial air in snow.^[128a] On the other hand, the observations of Mahajan et al.^[128c] indicate that the source of IO is the direct emission of iodine-containing compounds from open-water channels formed in the ice. The occurrence of open water will increase as the Arctic sea-ice continues to thin and retreat, which could enhance the rate of iodine flux to the atmosphere.

12. Marine Chemistry

The concentration of total dissolved iodine in seawater at 35 g dissolved solids per kg of seawater (abbreviated ppt or ‰) is about 450 nM. In oxygenated ocean waters, iodine exists primarily as iodate (the thermodynamically stable form of iodine) and iodide, which is kinetically stable to oxidation.^[139] In surface waters (upper 100 meters), iodide can constitute up to 50% of the dissolved iodine, but iodide rapidly decreases below this light penetration zone, with iodide approaching 1 nM in deep waters (with a corresponding increase in iodate).^[140] Coupling analytical methods that can specifically determine iodate^[141] and iodide^[140d,142] with a method to determine total iodine concentrations (e.g., inductively coupled plasma mass spectrometry, ICP-MS) indicate that non-volatile dissolved organic iodine (DOI) compounds^[143] can also exist as [I]_{DOI} = [I]_T – [I⁻] – [IO₃⁻], where [I]_T denotes the total iodine concentration. However, DOI compounds are mainly found in coastal areas of high primary productivity^[144] or oxygen-minimum zones^[145] (OMZs; where the oxygen concentration is ≤ 3 μM). In surface waters, DOI compounds can release iodide upon photochemical decomposition of the organic material.^[146]

The reduction of iodate to iodide has been of great interest because of iodide enrichment in surface waters. The oxidation of iodide to iodate^[139c] is a six-electron process and is complicated by the formation of molecular iodine, which at the pH value of seawater exists as HOI and adds iodine as I⁺ to organic matter.^[143,147] In oxygenated waters, phytoplankton reduce nitrate to ammonia with nitrate reductase, and this process has been suggested to reduce iodate.^[148] However, experiments using nitrate reductase to reduce iodate indicated that the process may not be a major process,^[149] but may depend on different phytoplankton species with differing abilities to reduce iodate.^[150]

In OMZs of the equatorial East Pacific Ocean,^[151] the Arabian Sea,^[140c,152] and the Orca Basin,^[153] as well as in sediments,^[154] oxygen is not detectable by most analytical methods^[155] and the reduction of iodate to iodide occurs

through bacterial decomposition of organic matter.^[106,140c,156] The free energy for this redox transformation is similar to that for nitrate reduction to N₂ during bacterial decomposition of organic matter^[154b,156] (denitrification). In anoxic basins (e.g. in the Black Sea) and brines containing sulfide, iodate is not detectable as it is converted into iodide.^[26,145,157] Iodate reduction in sediments and the subsequent return of iodide to the water column has been invoked as a mechanism for high iodide concentrations both in coastal zones^[158] and in the Arabian Sea.^[152]

The ratio of total dissolved iodine to salinity (I_T/Sal, or specific dissolved iodine) should be at a constant value of 12.8 nM‰⁻¹ if iodine behaves as a conservative element in seawater. However, the ratio is typically smaller in surface waters, thus indicating that some iodine is lost to the atmosphere as I₂ or volatile organic compounds (see Section 11), or is incorporated into particulate organic matter,^[159] which settles into ocean sediments. The incorporation of iodine into particulate organic matter, including algae, can occur as iodate is reduced or iodide is oxidized with the production of HOI, a versatile electrophilic reagent^[147] that leads to the formation of C–I or N–I bonds.^[160] The molar I/C ratio in algae in surface waters is close to 10⁻⁴:1.^[139a,159,161] but I/C is 10⁻³:1 or greater in deep ocean sediments,^[162] thereby indicating that iodine is transported from surface waters to bottom sediments as algal remains fall through the water column. During descent, some particulate iodine releases iodide to give the very low concentrations observed in the deep water.^[140a,b,d,156] Particulate iodine in sediments is then released to pore waters as iodide, at concentrations of several micromolar^[154,162a,b] and with a corresponding increase in the I_T/Sal ratio. The I_T/Sal ratio also increases in anoxic basins^[145,157b] and in brines,^[26] where the decomposition of organic matter occurs. Halide salt deposits form in brines at ten times the salinity of seawater.^[26,163] These deposits undergo equilibrium redissolution and reprecipitation. In the case of iodide, redissolution is enhanced and results in iodide enrichments above the normal I_T/Sal ratio.

Iodide oxidation normally requires reactive oxygen species or biological mediation (as in the haloperoxidases discussed in Section 10). The oxidation of iodide by MnO₂ has been described in laboratory reactions^[164] and may be responsible for the formation of iodate in sediments.^[162a,b] All iodide oxidation reactions lead to molecular iodine and HOI, with their concentrations dependent on the pH value of the system.

The marine chemistry of iodine is still revealing new twists and insights of iodine chemistry since the discovery of the element in seaweeds. The transformation between iodate and iodide is still an area for fertile research activity, as molecular iodine species are produced that can react with a host of inorganic and organic compounds and affect the cycling of other redox-active elements. The use of iodine isotopes as tracers for marine processes is also yielding important information.^[142b]

13. Geochemistry

With its unique geochemical behavior and isotopic system, iodine has many applications in geological sciences, from tracing fluid movement in the Earth's crust,^[165] dating meteorites,^[166] to characterizing the hydrological properties of soil.^[167] In the Earth's crust, more than >95% of the total iodine reservoir is contained in marine and terrestrial sediments, which only comprise 6–7% of the total crust materials.^[168] The large ion radius of iodide means that it is not readily incorporated into rock-forming minerals. This, combined with the volatility of iodine, results in iodine levels being consequently and consistently low in igneous rocks. Iodine enrichment in sediments is mostly related to organic matter, because marine organisms assimilate and accumulate iodine from seawater.^[139a,168] The decomposition of organic matter within sediments triggers changes in the chemical compositions of the pore waters and the sediments (diagenesis). Organic matter diagenesis releases iodine into the ambient pore water, which migrates and returns to the iodine reservoir in the seawater.^[162a]

As a consequence of this geochemical cycle, iodine concentrations in pore fluids were used to identify long-distance fluid movements in continental margins^[169] and the formation of methane hydrates.^[170] In addition, the cosmogenic iodine isotope system (¹²⁹I/¹²⁷I, referred to as the ¹²⁹I system) allows determination of the age of iodine in fluids (the elapsed time since the organic source of iodine was buried),^[168] which can be used to further pinpoint the geological source of fluids. The ¹²⁹I system has recently been applied to many methane hydrate fields^[171] and mud volcanoes^[172] in the forearc region of convergent continental margins, where oceanic crusts subduct under continents (e.g. the Pacific Rim). These results emphasize the importance of organic sources that are old (ca. 50 million years) and deeply buried (>5 km) in the upper plate, which slowly release iodine over geological time scales. In contrast, iodine in the volcanic fluids have ages similar to the lower plate, indicating rapid release of iodine from the subducted sediments^[173] on the oceanic plate. In contrast to the convergent margins, ¹²⁹I studies of passive continental margins remain rare.^[174] In addition to the naturally formed ¹²⁹I, the ¹²⁹I released from human activities (such as nuclear bomb tests and nuclear fuel reprocessing) has also increased the ¹²⁹I/I ratios by several orders of magnitude in surface reservoirs. The anthropogenic ¹²⁹I can be used as a tracer in oceanography.^[175] The transport of ¹²⁹I in the atmosphere, rivers, and soil,^[176] as a hazardous radionuclide, has also been an important aspect of this isotope system.

The chemical form of iodine (iodide and iodate) is related according to the prevailing redox conditions in modern seawaters and shallow pore waters. Synthesized calcium carbonate minerals were found to incorporate iodate, but not iodide, into the crystals.^[177] The concentration of iodate in carbonate is proportional to the iodate concentrations in ambient water, thus making the carbonate-bound iodine a proxy for redox changes over the geological history. Natural carbonates formed by biomineralization during a large-scale oceanic anoxic event (OAE) about 183 million years ago

(Toarcian OAE) contain much less iodine compared to those formed before or after the OAE, and the I/Ca ratios suggest that the oxygenation level in local waters during the OAE was probably similar to a modern strong hypoxic event.^[177]

Current knowledge about iodine provides the basis for a novel approach to investigating the coevolution of ocean redox^[177] and I-dependent antioxidant defense mechanisms.^[95] It is generally accepted that the Earth's surface became oxygenated during two major steps approximately 2 and 0.6 billion years ago.^[178] Several intriguing questions related to these changes have not been tackled so far. When did the seawater become sufficiently oxidized for iodate to be present? When did the I-dependent antioxidant mechanism first appear in the evolution of life? Is this evolutionary step triggered by the oxygenation of the ocean/atmosphere creating oxidative stress? How does the total iodine concentration in seawater change on a million to billion year time scale?

14. Radiochemistry of Iodine

Iodine has only one stable isotope, ¹²⁷I, which represents almost 100% of the naturally occurring iodine. However, 36 additional isotopes have been identified and can be considered as well characterized.^[8e] The properties of the most important ones are listed in Table 4. Radioactive isotopes of

Table 4: Overview of the most important iodine isotopes.

Isotope	Nuclear spin	Decay [MeV]	Product	Lifetime
¹²³ I	5/2	electron capture (1.4)	¹²³ Te	13.3 h
¹²⁵ I	5/2	electron capture (0.15)	¹²⁵ Te	59 days
¹²⁷ I	5/2	–	–	∞
¹²⁹ I	7/2	β ⁻ (0.189)	¹²⁹ Xe	1.57 × 10 ⁷ years
¹³¹ I	7/2	β ⁻ (0.970)	¹³¹ Xe	8 days

iodine are produced during the fission of uranium and plutonium, and some radionuclides can also be produced by using cyclotron radiation and a suitable target.^[8f] Radionuclides of iodine can be found on both sides of the stability line in the nuclide chart. Hence, both β⁻ and β⁺ (positron) emitting nuclides exist. The half-life of the most stable radioactive isotope, ¹²⁹I, is 15.7 million years, while the half-life of the second most stable isotope, ¹²⁵I, is only 59 days. Hence, most of the radioactive isotopes of iodine are fairly short lived. ¹²⁹I has a half-life that is too short for it to exist as a primordial nuclide, but excess amounts of its decay product, ¹²⁹Xe, have been found in meteorites, thereby proving its existence as primordial (from the origin of the Earth).^[179] The fact that its half-life is too short for it to exist naturally today puts it in the category of extinct primordial radionuclides. ¹²⁹I is produced by cosmic ray spallation of various xenon isotopes in the atmosphere and also during the fission of uranium and plutonium.^[180] Nuclear fuel reprocessing and atmospheric nuclear weapons tests have distorted the natural signal for this isotope.

The short half-lives of the remaining radionuclides of iodine makes them very suitable as tracers and therapeutic agents in medicine. The usefulness of a particular radionuclide depends on its half-life as well as on the type and energy of the decay.

As a result of the preferential uptake of iodine by the thyroid,^[8f,181] iodine radionuclides are extensively used in imaging and (in the case of ¹³¹I) destruction of dysfunctional thyroid tissues. Although ¹³¹I is one of the most stable radioactive isotopes of iodine and an important product of uranium fission, it is a β-emitting isotope with a half-life of eight days that forms the stable ¹³¹Xe isotope.^[8e] The average energy of the β radiation is 190 keV and the maximum energy is 606 keV. This is a fairly high energy, corresponding to a tissue penetration depth of 0.6 to 2.0 mm. The high energy β radiation from ¹³¹I is also the reason why this isotope is considered to be the most carcinogenic of the iodine isotopes. Consequently, it is assumed to cause the majority of the excess thyroid cancers seen after contamination by nuclear fission (e.g., bomb fallout and severe nuclear reactor accidents).

¹²³I and ¹²⁵I (half-life of 13 h and 59 days, respectively) are γ (photon) emitters and are, therefore, used in nuclear imaging (mainly of the thyroid).^[8f] ¹²⁵I is also used in low dose rate brachytherapy, in particular for prostate cancer. As a consequence of its relatively long half-life and low energy gamma radiation, ¹²⁵I is also employed in assays where iodine is used as a tracer.^[84b]

¹²⁴I can be used to directly image the thyroid by using positron emission tomography (PET). The isotope can also be used as a PET tracer incorporated in a radiopharmaceutical.^[182] The main advantage is its longer half-life compared to ¹⁸F.

¹³⁵I is a common isotope in nuclear reactor physics.^[8f] It has a relatively high fission yield (6.3%) and decays to ¹³⁵Xe with a half-life of 6.57 h. ¹³⁵Xe is a nuclear poison due to its very large cross-section of thermal neutrons. The buildup of ¹³⁵Xe can cause severe problems when restarting a reactor after shut down. ¹²⁸I, ¹³⁰I, ¹³²I, and ¹³³I are also fission products with half-lives ranging from minutes to a couple of hours. Their short half-lives mean they are essentially of no practical use.

The Fukushima nuclear accident on 11 March 2011 was a direct consequence of an earthquake and, in particular, the following tsunami.^[183] Radionuclides were released and contaminated the marine environment. This occurred through atmospheric fallout or washout with precipitation and through discharges of contaminated water into the sea. The release of radioactive material to the atmosphere has been estimated to be approximately 10% of the Chernobyl accident. The activity of ¹³¹I around 30 m from the point of discharge was reported to be approximately 10⁵ Bq L⁻¹. In offshore waters, 30 km from the point of discharge, the maximum level was around 80 Bq L⁻¹. As a point of reference, the maximum allowed ¹³¹I activity for milk and drinking water in Japan is 300 Bq L⁻¹ for adults and 100 Bq L⁻¹ for children. The levels close to the point of discharge were indeed alarming when the maximum value was reached, but as a consequence of dilution and the fairly short half-life, the impact of ¹³¹I on the marine environment must be considered

as local. Less than a month after the maximum value was reached, the activity level 30–330 m from the point of discharge was below 500 Bq L^{-1} . It should be noted that the release of ^{134}Cs and ^{137}Cs will have an impact on the environment for a considerably longer time because of their longer half-lives of 2.1 and 30.2 years, respectively.^[8e] Consequently, significantly larger areas will be affected by these nuclides and contamination will remain for longer times.

15. Summary and Outlook

The number of scientists working on, and the overall funding available for, iodine-related research is currently probably unprecedented in the two centuries of studies on this element. In terms of public health, reaching the third of the global population that remains iodine deficient poses major challenges, and iodine deficiency remains one of the most important causes of preventable mental retardation worldwide. In the atmosphere, recent research suggests that iodine from natural oceanic sources plays a widespread role, from surface ozone destruction in polar regions, through aerosol formation in coastal regions, to a possibly global role in modifying ozone and oxidant levels over the open ocean. In the ocean, the iodide–iodate transformation still offers challenges to biological and chemical oceanographers. The exploration of the biogenic, evolutionary origin of the high iodine levels encountered in marine sediments requires more, probably interdisciplinary, research efforts. Iodine also plays an increasingly important role in the synthesis of new organic and inorganic substances and materials, as well as main components in electrochemical devices, such as third generation solar cells.

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