Iodine speciation in nuclear industry.

Presented by D. Doizi.

CEA, DEN/DANS/DPC/SECR/LRMO, Saclay, France.

Outline of the talk:

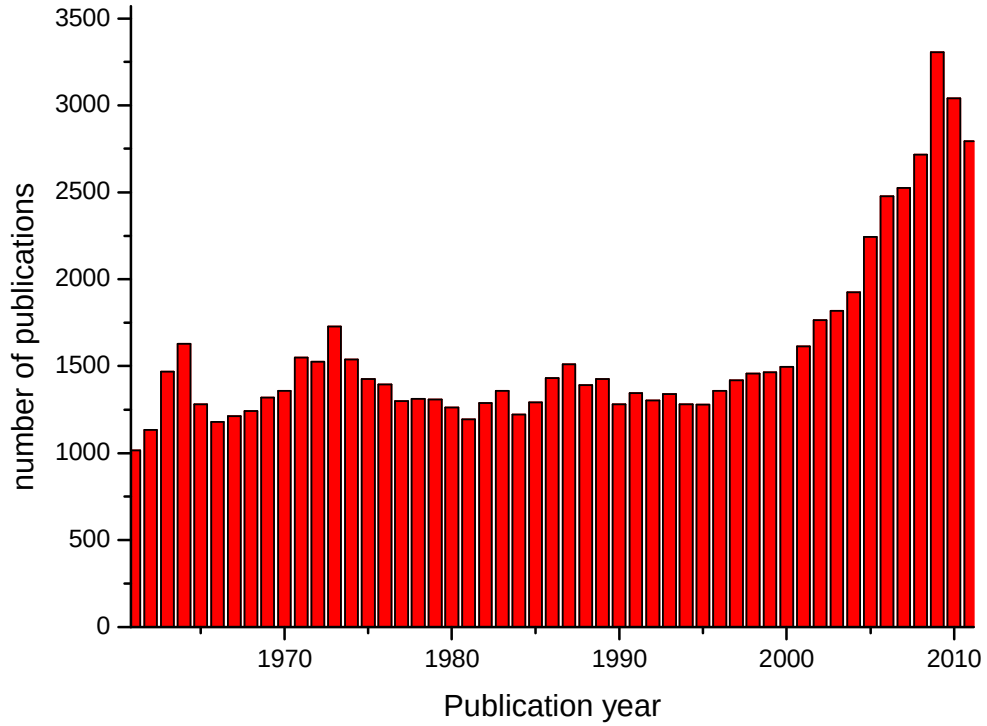
- **Introduction.**
- **Back to basics on the element I.**
- **Speciation of iodine in solution.**
- **Speciation of iodine in the gaseous phase.**
- **Speciation of iodine in the solid phase and imaging.**
- **Conclusions.**

Introduction.

This talk is a review of iodine speciation in the nuclear industry and presents some experimental work done at the Nuclear Energy Division and especially in our laboratory.

energie atomique • energies alternatives

<u>Iodine</u> : 257953 references on SciFinder (3/05/2012) of which 76103 references for stable I-I (CAS number 7553-56-2).



Introduction.

Iodine is a very important element which is present in numerous and various domains of our life.

energie atomique • energies alternatives

• ***Environmental domain*:**

From the geosphere to the biosphere : soils, air, sea (450 nM [I_2], brown algae Laminaria Digitata, strongest accumulator of iodine among all living systems).

• ***Medecine and physiology:***

Tissues, urine, colon, thyroïd where it plays an important role in the endocrine system.
The body of a healthy adult contains up to 20 mg iodine which 70-80% is in the thyroid.
It is used as a disinfectant in aqueous solution (tincture of iodine).

• ***Nuclear industry:***

Iodine is a fission product released in the case of severe nuclear accidents.
It is present under volatile forms (molecular iodine, organic iodides) or under the form of aerosols (metal iodides).
Iodine is released at the dissolution of irradiated nuclear fuels.
Iodine is involved in the massive hydrogen production using iodine sulphur water splitting cycle.

The knowledge of iodine chemistry as well as its speciation are of utmost importance. Analytical techniques for iodine speciation are transverse.

Back to Basics on the element I

Iodine element belongs to the halogen family. Group 17 of the PTable
Discovered by B. Courtois in 1811, from the greek ἰώδης (violet).
Physical properties of the element:

- 53 electrons ($5s^2\ 5p^5$)
- numerous isotopes: 108 à 144

The more stable isotopes

Isotope	Period	Decay mode	Energy, MeV
123 I	13.2235 h	α, γ	0.16
125 I	59.4 j	α, γ	0.0355
127 I	stable		
129 I	15.7 Ma	β-	0.194
131 I	8.0207j	β-, γ	0.971

Medical applications
(labeling, curietherapy,…)

Nuclear domain

Similar to the other halogens, the valence electron configuration renders I_2 molecule the stable state of the element with a direct and single I-I bond.

Isotopic abondance of iodine

Elem. or Isot.	Natural Abundance (Atom %)	Atomic Mass or Weight	Half-life/ Resonance Width (MeV)	Decay Mode/ Energy (/MeV)	Particle Energy/ Intensity (MeV/%)	Spin ($h/2\pi$)	Nuclear Magnetic Mom. (nm)	Elect. Quadr. Mom. (b)	γ-Energy / Intensity (MeV/%)
									0.7228/10.3
									1.6910/11.2
									(0.31−1.73)
^{125}I		124.904630	59.4 d	EC/0.1861		5/2+	2.82	-0.89	Te k x-ray
									0.0355
^{126}I		125.905624	13.0 d	EC/		2-	1.44		ann.rad./
				β+ /2.155	1.13/				Te k x-ray
				β- /1.258/47	0.87/				0.3887
					1.25/				0.6622
^{127}I	100.	126.904473				5/2+	+2.8133	-0.79	
^{128}I		127.905809	25.00 m	β- /2.118	2.13/	1+			Te k x-ray
									0.44287
									0.52658
^{129}I		128.904988	1.7×10^7 y	β- /0.194	0.15/	7/2+	+2.621	-0.55	Xe k x-ray
									0.0396
^{130m}I			9.0 m	I.T./83/0.048		2+			I k x-ray
				β- /17/					0.5361
^{130}I		129.906674	12.36 h	β- /2.949	1.04/	5+	3.35		0.4180
					0.62				0.5361
									0.6685
									0.7395
^{131}I		130.906125	8.021 d	β- /0.971	0.606/	7/2+	+2.742	-0.40	0.08017
									0.28431
									0.36446
									0.63699
^{132m}I			1.39 h	IT		8-			
^{132}I		131.90800	2.28 h	β- /14/3.58	0.80/	4+	3.09	0.09	I k x-ray
				I.T./86/	1.03/				0.0980
					1.2/				0.5059
					1.6/				0.52264
					2.16/				0.63019
									0.6506

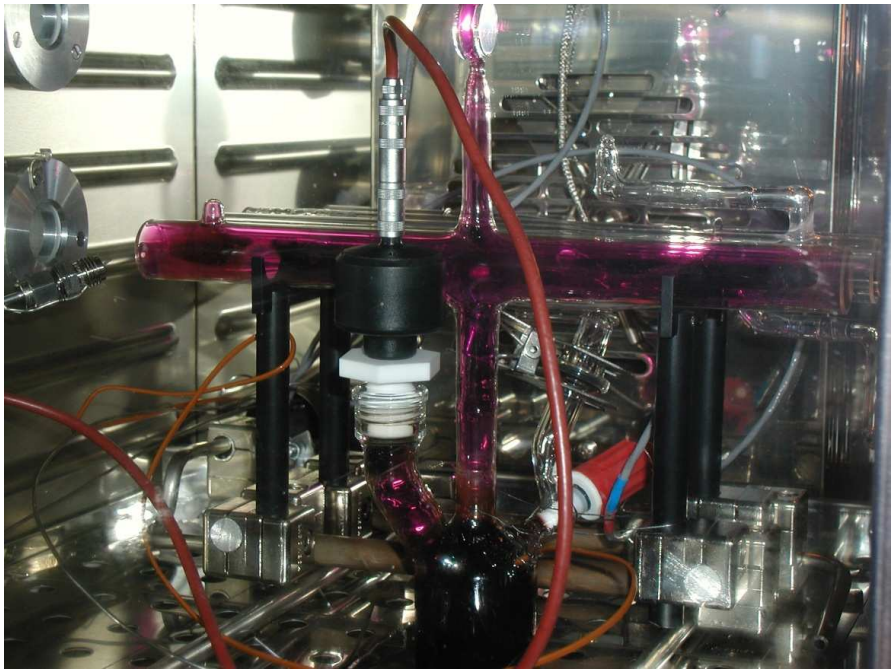
Iodine, a « sticky » molecule.

Black solid with metallic blue grey reflets. (Brown algae have been used as the raw material for iodine production at the origin. Today, the production comes from Chile (2/3) caliche deposits and Japan (1/3) brines from natural gas).

Fusion T°: 113,7°C

Boiling T°: 184.4°C

It sublimates at the ambiant temperature.



Violet vapors of iodine observed around 120°C

Iodine in solution: an extensive chemistry.

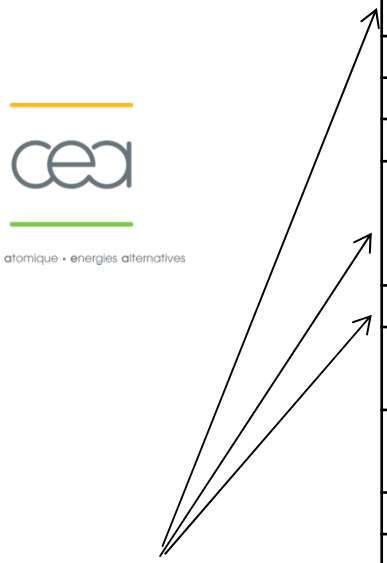
Iodine solubility in water is low: $2.68.10^{-3}$ mol.L^{-1} at 25°C.
Iodine molecule dissolves in organic solvents and gives different colored solutions. I_2 accepts electrons from the solvent molecule into its LUMO. This lowers the energy of the transition HOMO-LUMO thereby changing the color.

From Atkins, Jones
Principles of chemistry

Iodine molecule solubility is increased in the presence of I^- ions thanks to the reaction:
$I_2 + I^- \longrightarrow I_3^-$ Polyiodates formation.

Iodine electronegativity is lower than the one of the other halogens.
Oxydant reagent which can also be oxydized.
Iodine has many oxydation states ranging from -1 to +7.

The different oxydation states of iodine in solution



Oxidation state	Species	State	Name
-1	HI	gaseous	hydroiodic acid
	I^-	dissolved	iodide anion
	I_3^-	dissolved	Triodide anion
	I_5^-	dissolved	Pentaiodide anion
0	I_2	solid dissolved gaseous	Iodine
+1	I^+		
	HOI	gaseous dissolved	Hypoiodous acid
	H_2OI^+	dissolved	Hypoiodous acidium cation
	OI^-	dissolved	Hypoiodite anion
+3	HIO_2	dissolved	Iodous acid
	IO_2^-	dissolved	
+4	I_2O_4	solid	diiodinetetroxide
	I_4O_9	solid	Tetraiodine nonaoxide
+5	HIO_3	dissolved solid	Iodic acid
	IO_3^-	dissolved	Iodate anion
	IO_2^+	dissolved	
	I_2O_5	solid	Diiodine pentoxyde
+7	HIO_4	dissolved solid	Periodic acid
	IO_4^-	dissolved	Periodate anion
	HIO_5^{2-}	dissolved	
	IO_5^{3-}	dissolved	

Some basics on oxydo reduction reactions

Initially, an oxydation reaction is the combination of an element with oxygen (oxydant).

Ex : $2Na + 1/_2O_2 \rightarrow Na_2O$

A similar result is obtained with other compounds such as F_2, Cl_2, S.

Ex: $Na + 1/_2Cl_2 \rightarrow NaCl$

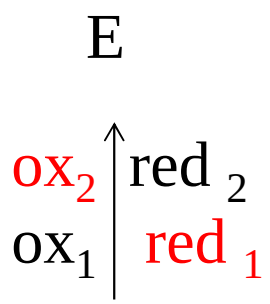
More generally, an oxydation reaction leads to a loss of electrons.
An oxydant is a substance which accepts electrons (O_2, Cl_2, …).
A reductant is a substance which gives electrons (Na, H_2, C, …).

The reaction $Na + 1/_2Cl_2 \rightarrow NaCl$ can be written:

$1/_2Cl_2 + e^- \leftrightarrow Cl^-$ or $ox_2 + n_2e^- \leftrightarrow red_2$
$Na \leftrightarrow Na^+ + e^-$ or $red_1 \leftrightarrow ox_1 + n_1e^-$

The final balance is:

$n_1ox_2 + n_2\ red_1 \leftrightarrow n_2ox_1 + n_1red_2$

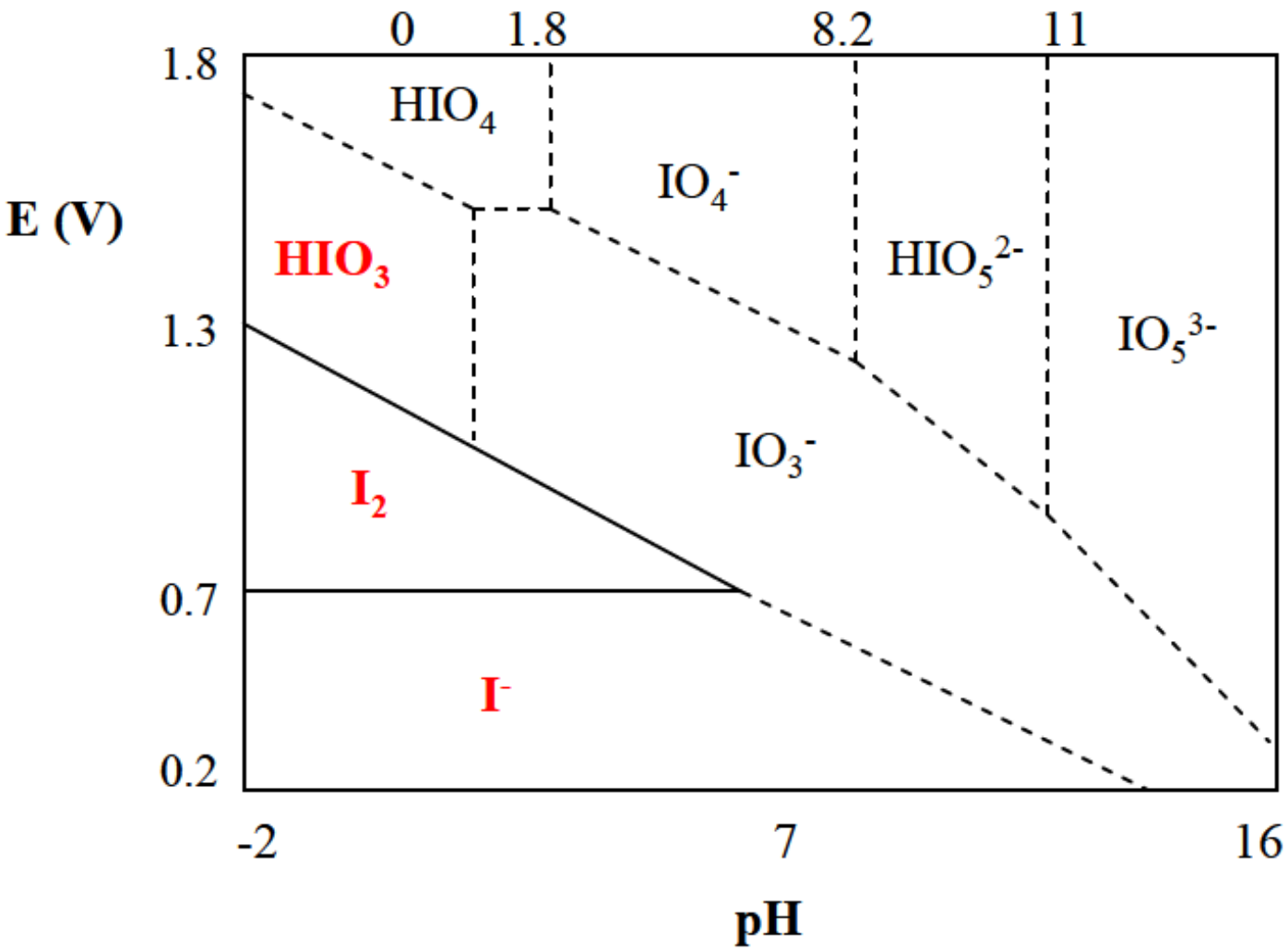


Standard Potentials for iodine and its major derivatives at 25°C vs HSE.

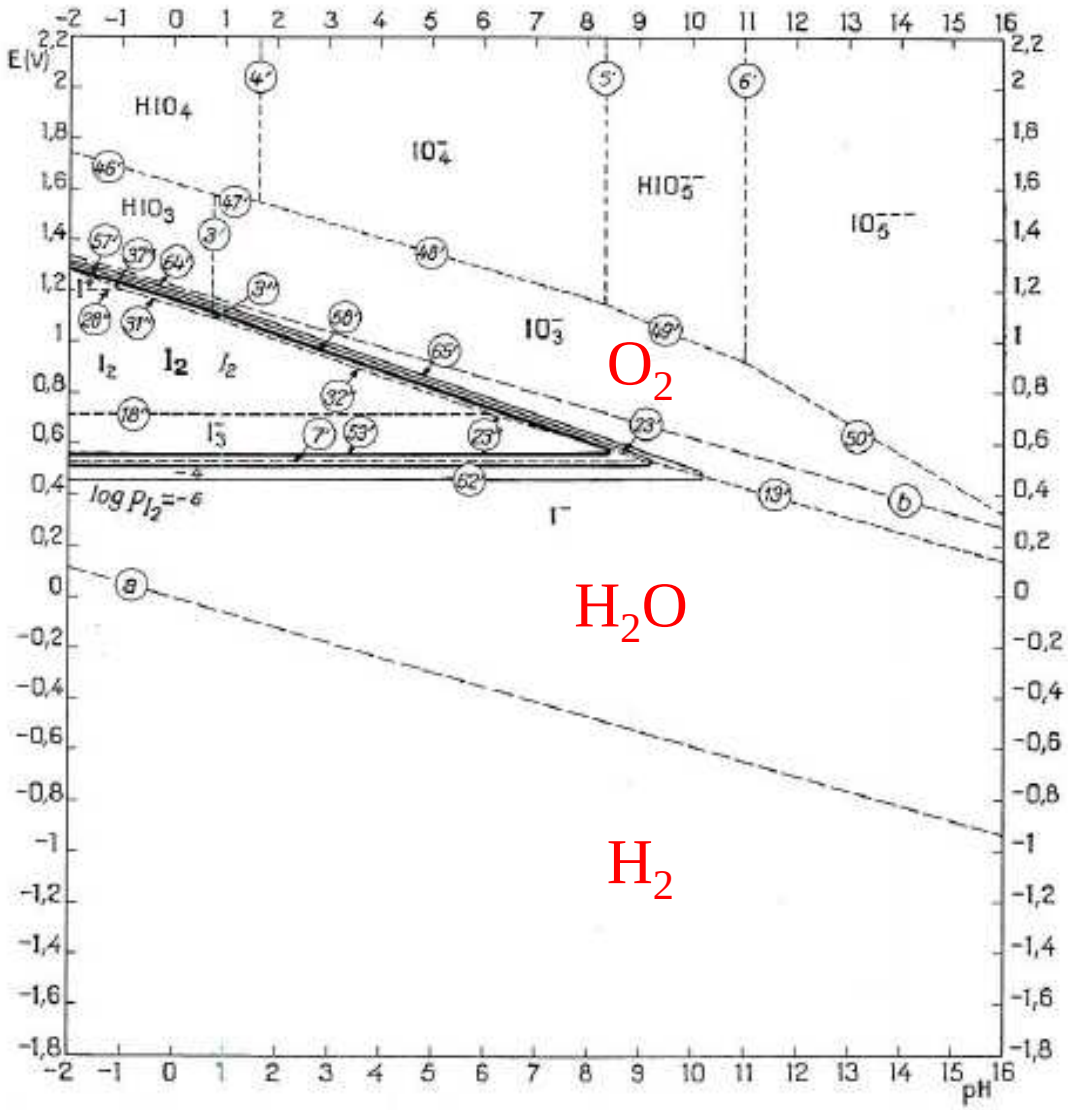
Couple redox	Equation redox	E° (V/ESH)
I_2/I^-	$I_{2(solide)} + 2\,e^- \rightarrow 2\,I^-$	0,535
	$I_{2(aq)} + 2\,e^- \rightarrow 2\,I^-$	0,621
I_3^-/I^-	$I_3^- + 2\,e^- \rightarrow 3\,I^-$	0,536
I_2/I_3^-	$3\,I_2 + 2\,e^- \rightarrow 2\,I_3^-$	0,782
HOI/I^-	$HIO_{(aq)} + H^+ + 2\,e^- \rightarrow I^- + H_2O$	0,985
H_2OI^+/I^-	$H_2OI^+ + 2\,e^- \rightarrow I^- + H_2O$	0,940
OI^-/I^-	$IO^- + H_2O + 2\,e^- \rightarrow I^- + 2\,OH^-$	0,472
HOI/I_2	$2\,HIO + 2\,H^+ + 2\,e^- \rightarrow I_2 + 2\,H_2O$	1,351
H_2OI^+/I_2	$2\,H_2OI^+ + 2\,e^- \rightarrow I_2 + 2\,H_2O$	1,261
OI^-/I_2	$2\,IO^- + 4\,H^+ + 2\,e^- \rightarrow I_2 + 2\,H_2O$	1,354
IO_3^-/I_2	$2\,IO_3^- + 12\,H^+ + 10\,e^- \rightarrow I_{2(aq)} + 6\,H_2O$	1,195
	$2\,IO_3^- + 12\,H^+ + 10\,e^- \rightarrow I_{2(solide)} + 6\,H_2O$	1,195
IO_3^-/I^-	$IO_3^- + 3\,H_2O + 6\,e^- \rightarrow I^- + 6\,OH^-$	0,257
IO_3^-/OI^-	$IO_3^- + 4\,H^+ + 4\,e^- \rightarrow IO^- + 2\,H_2O$	0,972
IO_3^-/HOI	$IO_3^- + 5\,H^+ + 4\,e^- \rightarrow HIO + 2\,H_2O$	1,134

From C. Cau Dit Coumes, phD Thesis.

Potentiel pH diagram of iodine



Pourbaix diagram of iodine at 1atom gram/l



Stability diagram of water.

Couples H_2O/H_2 and O_2/ H_2O

$H^+ + e^- \rightarrow 1/_2H_2$
E = -0.06 pH

$1/_2O_2 + 2e^- + 2H^+ \rightarrow H_2O$
E = 1.23 – 0.06pH

From M. Pourbaix, atlas d'équilibres électrochimiques, chap 4, section 20.4, 614-626, (1963).

Iodine Species predominance diagram vs pH, in water

Predominant and stable iodine species are: I_2, I^- , I_3^-, HOI, IO_3^-

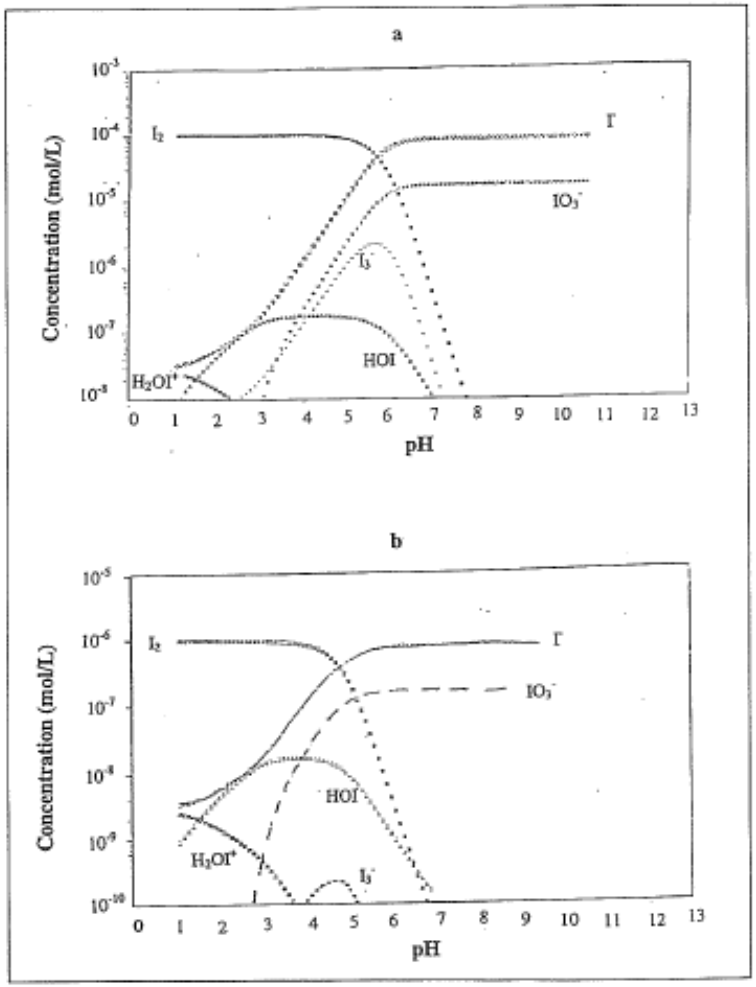


Figure II-5 : Courbes de répartition à 25°C des espèces formées par hydrolyse de l'iode en fonction du pH du milieu.
A : concentration initiale d'iode : 10^{-4} mol.L^{-1}
B : concentration initiale d'iode 10^{-4} mol.L^{-1}

From C. Cau Dit Coumes,phD Thesis

Major reactions of iodine and iodates.

Iodine is only stable in acid slightly oxydant solutions.
When the pH reaches neutrality, iodine hydrolyses.

The dismutation (disproportionation, hydrolysis) of iodine in water:

$$I_2 + H_2O = HOI + I^- + H^+$$

Hypoiodous acid HOI is a non stable thermodynamic amphoter compound:

$$3HOI \rightarrow IO_3^- + 2I^- + 3H^+$$

In alcaline media, (pH>8), iodine dismutes rapidly and totally:

$$3\ I_2 + 3\ H_2O \Leftrightarrow IO_3^- + 5\ I^- + 6\ H^+$$ **(inverse Dushman reaction)**

The slow oxydation of I^- by dissolved oxygen:

$$2I^- + \tfrac{1}{2}O_2 + 2H^+ \leftrightarrow I_2 + H_2O$$

Analytical techniques for iodine speciation.

Analytical techniques to study iodine species:

energie atomique • energies alternatives

- Classical spectrophotometric techniques
- Precipitation titrations
- Atomic Absorption Spectrometry
- Neutronic Activation
- X ray absorption (XANES, EXAFS) and fluorescence
- ICP mass spectrometry and hyphenated techniques
- Electrochemical and potentiometric techniques
- Scintillation measurements for radiotracers
- Mössbauer spectroscopy (^{129}I)

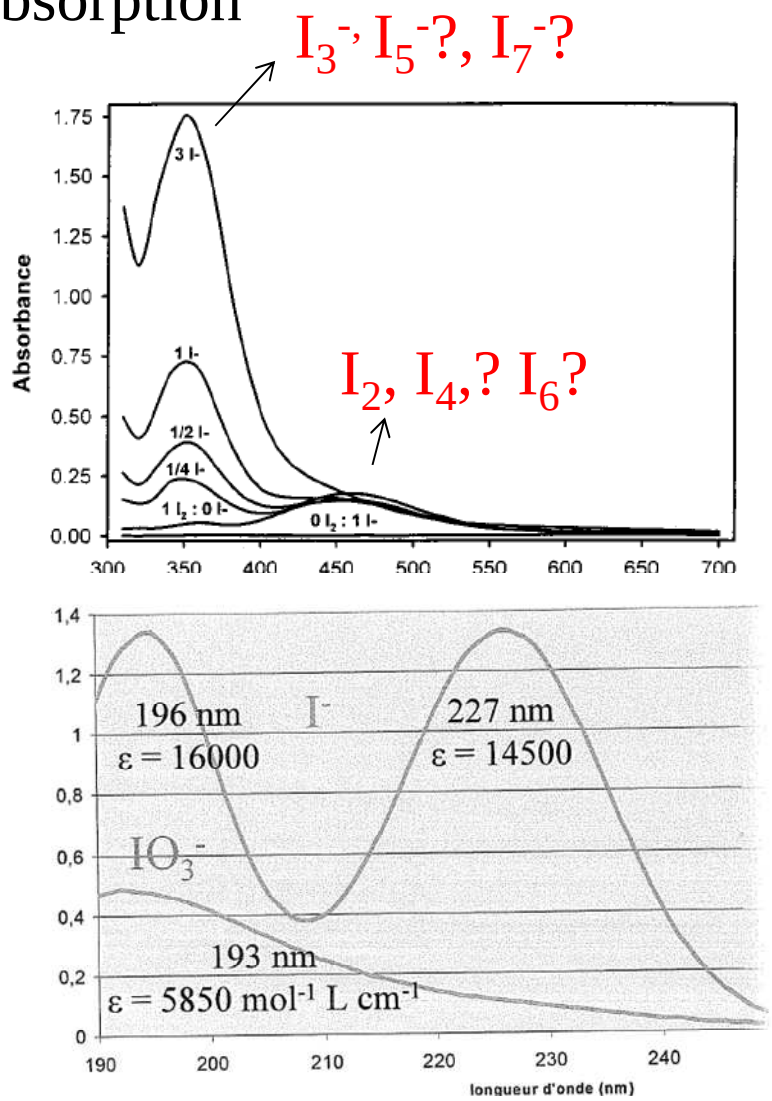
Recent review: Review of analytical methods for the quantification of iodine in complex matrices, C. P. Shelor, P. K. Dasgupta, Anal., Chim., Acta, 702 (2011) 16-36.

Comprehensive Handbook of iodine, Edited by Victor Preedy, Gerard Burrow, Ronald Watson. (2009) .

Analytical determination of iodine species in solution.

Optical spectrometry : UV –Visible absorption

Species	Wavelengths (ε,molar extinction coefficient)
I_2	470 nm (ε=790) 205 nm (ε=20000)
HOI	207,5 nm (ε= 9680)
I_3^-	350 nm (ε= 25700)
IO^-_3	207,5 nm (ε=4000)
I^-	225 nm (ε= 14400)



In nitric medium

Analytical determination of iodine species in solution.

Optical spectrometry: Raman diffusion

Table 2. Raman vibrational frequencies observed experimentally for I_3^-, I_5^- and I_2 in various samples

compound	mode designation	sample examined	wavenumber (cm-1)
I_3^-	v2, bending deformed linear I_3^-[14]	various solutions	70-80
	vI-I stretching (D2'bond) of HI_3* [8]	HI-I_2 solutions (1:1) in water	84
	v1, symmetric stretching linear I_3^- [14] [23] [21] [22]	various solutions	103-114
	v3, asymmetric stretching linear I_3^-[7]	(dbcr)I3 in the solid state	125
		(R3S)I3 solid2	145
		various solutions	143-152
	2v2, Fermi Resonance [8]	HI-I_2 solutions (1:1) in water	150
	vI_2 stretching (D1'bond) of HI_3* [8]	HI-I_2 solutions (1:1) in water	170-172
	vI_2-I_5 mode in I_5^- (I_3^- disproportion) [7]	(R3S)I3 liquid	170
	2v1, Fermi Resonance [8]	various solutions	220
I_5^-	vI_3-I_5, stretching of I_3^- in L-shaped I_5^- [7]	(dbcr)I5[1]	112
	vI_3-I_5, stretching of I_3^- moiety in I_5^- [14]	various samples	104-120
	vI_3-I_5, asymmetric stretching of I_3^- in L-shaped I_5^- [7]	(dbcr)I5[1]	143
	vI_5, bent I5- [7]	Polyvinylalcool thin film	140
	vI5, linear I5-[7]	iodine doped PVA	155
	vI5, linear I5-[24]	various solutions	164
	vI_2-I_5, stretching of I_2 unit in I_5^-	(R3S)I5 liquid3	170
		(dbcr)I51	168
		various solutions [16]	160-187
I_2	vI_2 stretching of free I_2 molecule [16]	I_2 in Me2SO	189
		I_2 in CHCl3	207
		I_2 in benzene	209
		pure I_2 solid [25]	180
		pure I2 molten [21]	194
		pure I_2 vapor [25]	216

1,(dbcr)= dibenzo-18-crown-6; 2,(R3S)I3= alkylsulfur triiodide; 3,(R3S)I5= alkylsulfur pentaiodide

From Iodine compounds speciation in HI-I2 aqueous solutions by Raman spectroscopy, Spadoni et al., IJHE, vol37, issue2, (2012), 1326-1334.

Analytical determination of iodine species in solution.

Quantitative Analytical Chemistry:

G. Charlot, D. Bézier, méthodes modernes d'analyse quantitative minérale, Masson éditeurs.
P. Jaulmes, précis de chimie analytique, tome 1, 1965.

energie atomique • energies alternatives

Titration of iodine by volumetric methods: with sodium thiosulfate (with starch, formation of a blue compound) :
1ml of thiosulfate 0.1N is equivalent to 12.69 mg of iodine.

Titration of iodide anions by volumetric methods using silver.
Precipitation of silver salts.

- **Volhard method,**
- **Mohr method,**
- **Fajans method.**

Iodide anions titration by potentiometry:
Titration using a I^- selective electrode.

Determination of total iodine concentration by ICP-MS.

The use of a plasma torch coupled with a magnetic mass spectrometer (ICP-MS) or optical emission spectrometry (ICP-OES) enables the mesurement of iodine traces.

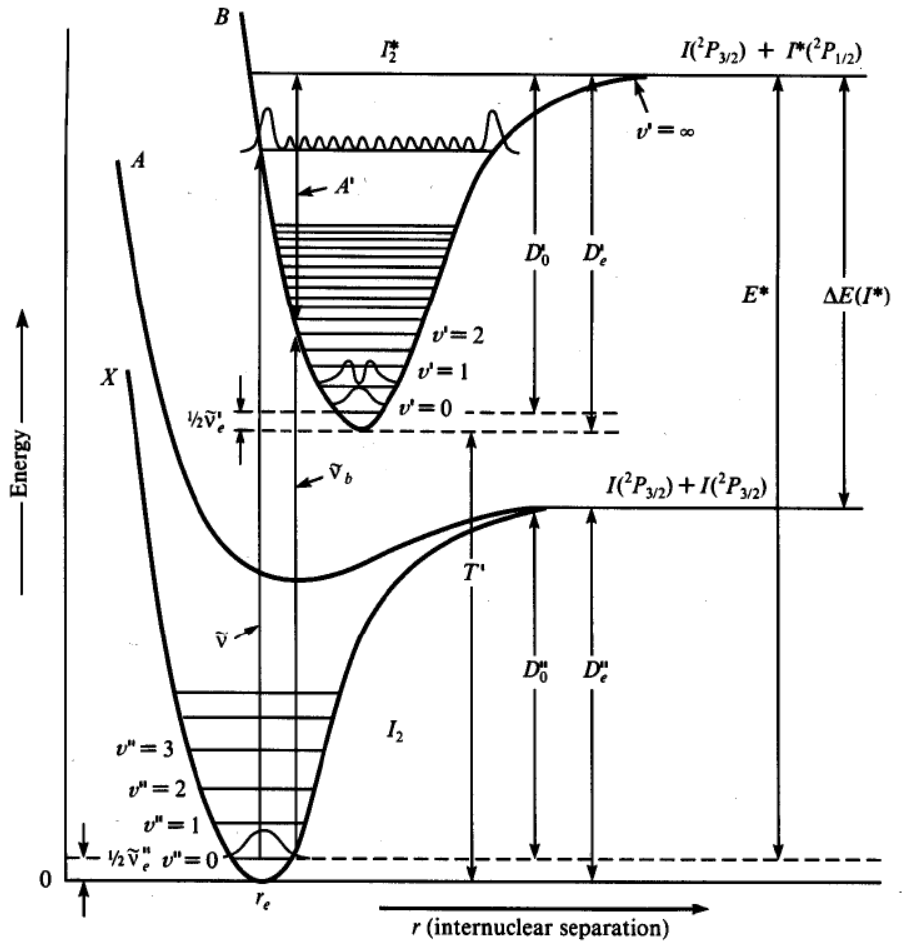
- Importance of the sample preparation.
- The choice of an alcaline medium increases the sensitivity.
- Iodine is difficult to ionize, use of ascorbic acid, reducing agent to study iodide anions (phD Thesis B. Langlois, DEN, 2001).
- Caution to memory effect in the nebulizer

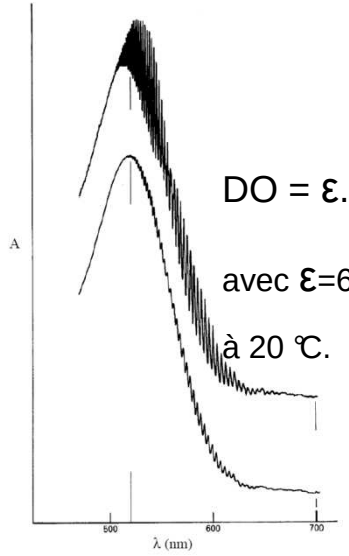
- **Review article:**

Iodine determination by ICP spectrometry, A.A Oliveira, L. C. Trevizan, J. A. Nobrega, Appl. Spect. Rev., 45:6, (2010), 447-473.

Iodine speciation in the gaseous phase

Violet colored vapor easily detectable in optical absorption spectrometry: UV Visible for example.

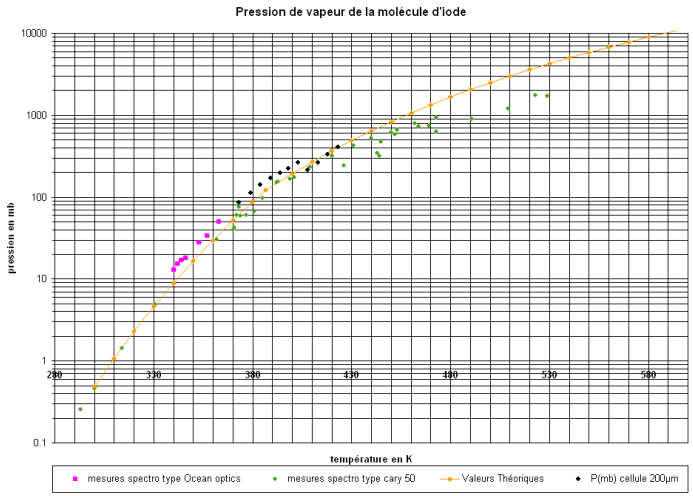




DO = ε.L.C

avec ε=691 $Lmol^{-1}cm^{-1}$

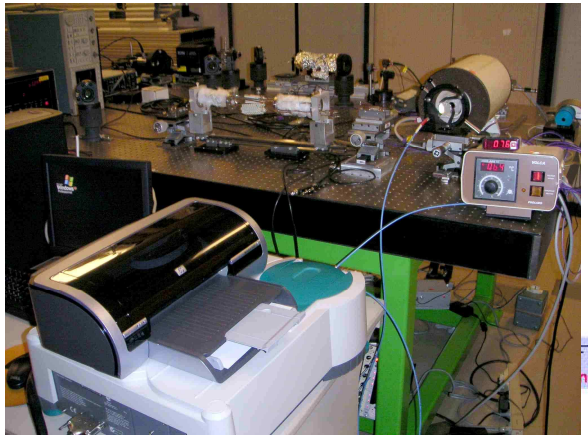
à 20 °C.

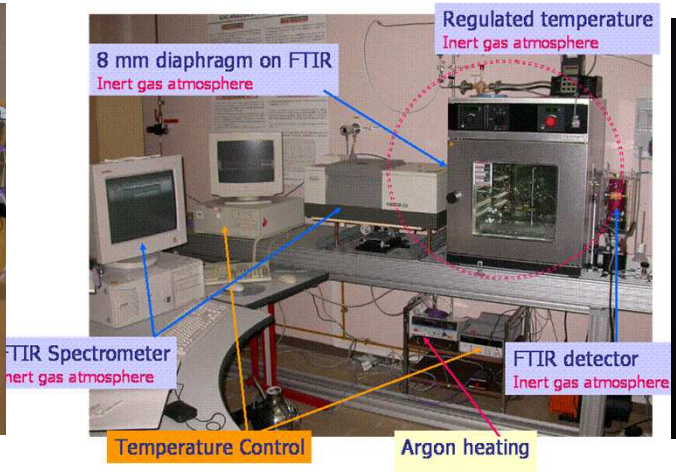


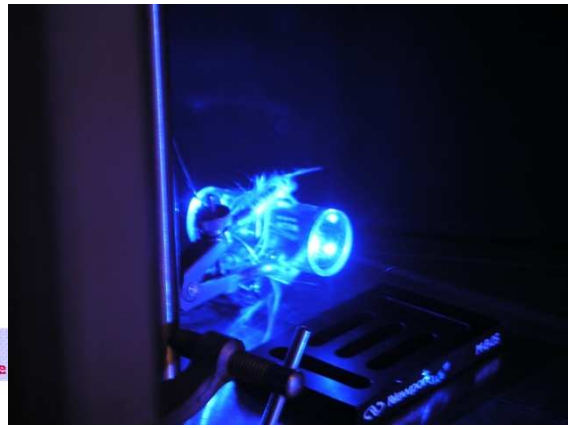
Iodine species in the iodine sulfur thermochemical cycle

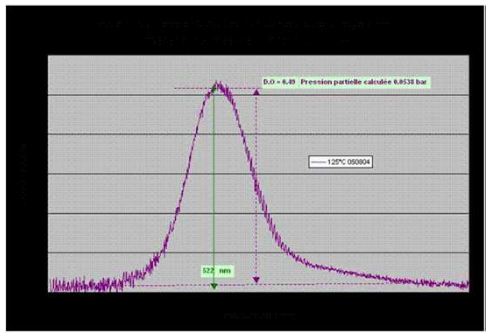
Liquid vapour equilibrium measurements are made using optical « online » techniques, to avoid tedious experiments and prevent any vapour composition changes.

- **HI (and H_2O): FTIR spectrometry**
- **I_2: UV-Visible spectrometry**
- **HI, (H_2O and H_2): Evaluation of Raman techniques.**

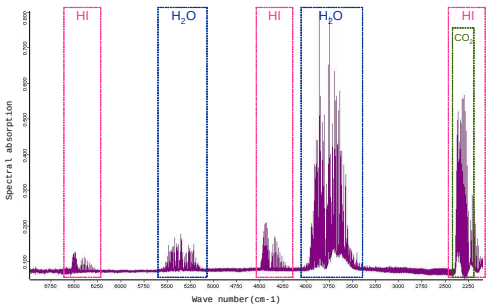


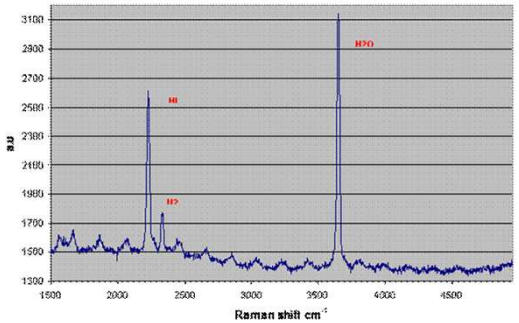






Spectral regions for the HI and H_2O vapours.



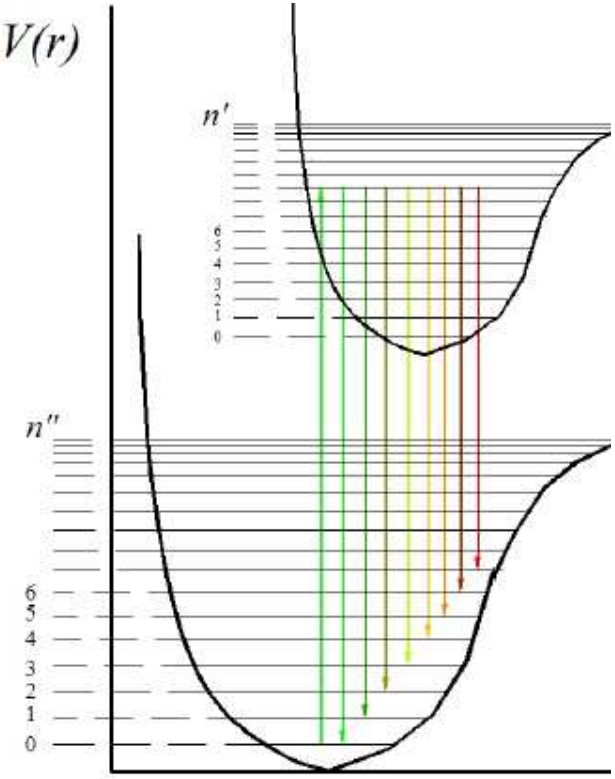


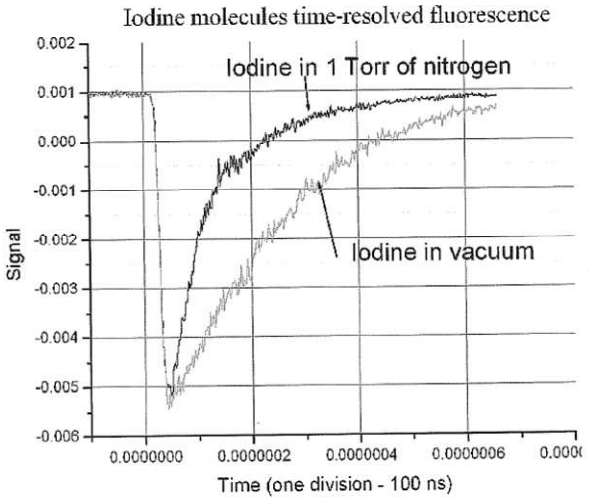
UV/Visible absorption **FTIR spectrometry** **Raman techniques**

Iodine speciation in the gaseous phase

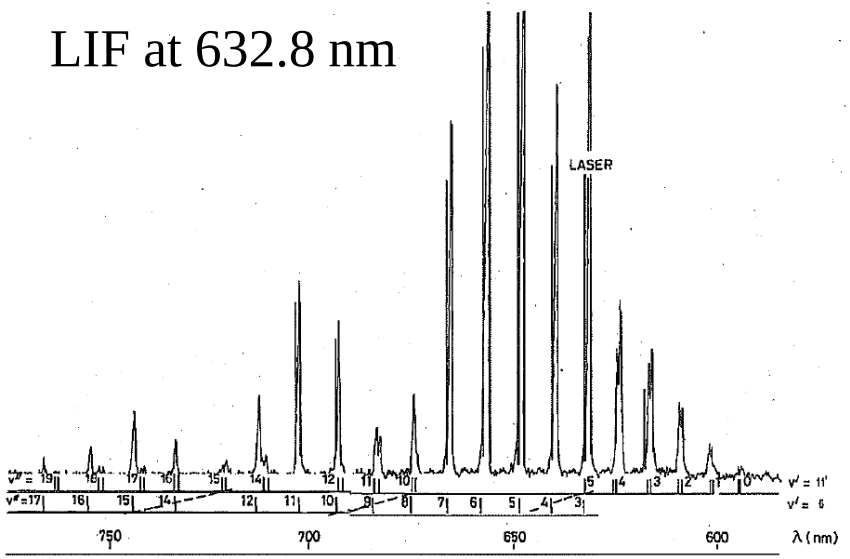
Violet colored vapor detectable in emission: laser induced fluorescence, spontaneous Raman diffusion. But low concentration only, otherwise fluorescence quenching.

energie atomique • energies alternatives





LIF at 632.8 nm



Gaseous iodine detection by colorimetry

Colorimetric method developped by Iwasaki (1952):

Reduction of iodine in iodide anions after bubbling iodine gas in a 1N NaOH solution.

A New Microdetermination of Iodide by its Catalytic Reaction

By Iwaji IWASAKI, Satori UTSUMI and Takejiro OZAWA

(Received August 26, 1952)

The authors found that the orange color of ferric thiocyanate which was formed by dilute potassium thiocyanate and an excess of ferric salt in dilute nitric acid solution, faded very slowly owing to the oxidation of thiocyanate, but rapidly in the presence of minute amounts of iodide.

The catalytic action of iodide on this reaction was studied colorimetrically, and a new microdetermination of iodide was accomplished.

Iodine also catalyzed the fading of ferric thiocyanate in exactly the same way as iodide, but chloride and bromide did not. In preliminary experiments it was found that this catalytic reaction was greatly affected by the presence of small amounts of nitrite. The reaction rate depended not only on the concentrations of iodide present, but also on the concentrations of thiocyanate and nitric acid, and especially on the temperature (Fig. 1).

Therefore these factors must be kept constant for iodide determination.

The determination of iodide could be made by measuring the absorbancy in a definite period of time and using the calibration curves (Fig. 1) previously obtained under the same conditions.

Procedure and Results:

To 10 cc. of the sample solution, 1.0 cc. of mixed reagent (3×10^{-3} or 10^{-3} M in potassium thiocyanate, 3×10^{-4} M in sodium nitrite) and 2.0 cc. of ferric alum reagent (prepared by dissolving 6 g. of ferric alum in 100 cc. of 5.7 N nitric acid) were added. The absorbancies were plotted against

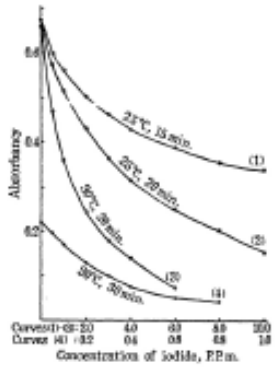


Fig. 1.—Calibration curves of iodide.
Curves (1)–(3): 3×10^{-3} M SCN^-
Curve (4): 10^{-3} M SCN^-

the concentrations of iodide as shown in Fig. 1.

The absorbancy was determined by a Beckman Model DU spectrophotometer at 460 mμ using 10 mm. cell. The calibration curves shown in Fig. 1 were reproducible within ± 5%.

The determination of iodide in concentrations of 0.5—10 p.p.m. could be made under the following conditions: 3×10^{-3} M SCN^-, 25°C., 20 minutes (Curve 2). The determination of iodide in concentrations of 0.05—0.8 p. p. m. could be made under the following conditions: 10^{-3} M SCN^-, 30°C., 30 minutes (Curve 4).

It was also possible to determine 0.001—0.05 p. p. m. of iodide under the following conditions: 10^{-3} M SCN^-, 45°C, 30 minutes.

By this method 0.001—10 p. p. m. of iodide could be determined in the presence of chloride and bromide.

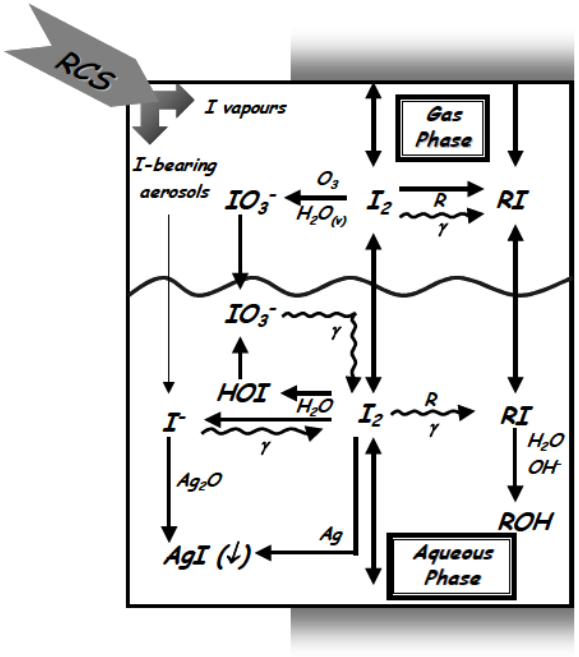
Laboratory of Analytical Chemistry and Geochemistry, Tokyo Institute of Technology, Tokyo

(1) I. Iwasaki, S. Utsumi and T. Ozawa, This Bulletin, **25**, 226 (1952).

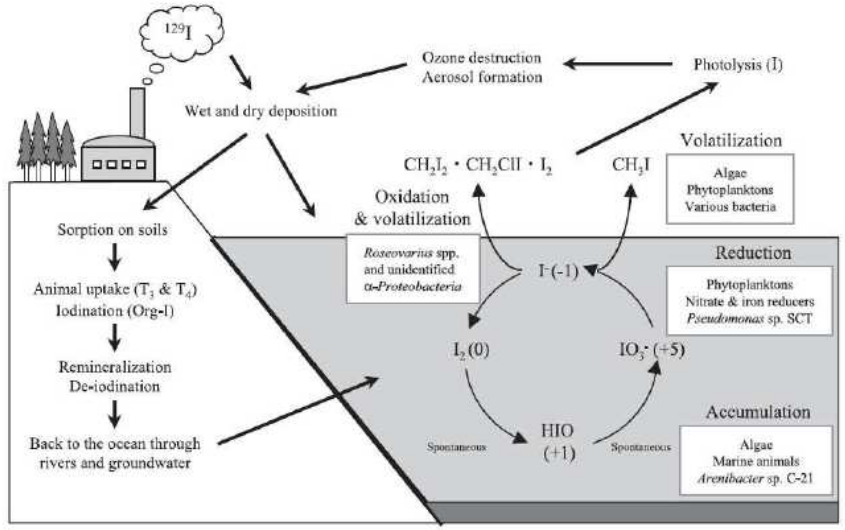
Special attention to organic iodides

Ex : Methyl iodide is very volatile: CH_3I is formed by the interactions between iodine and organic compounds such as oils, paints,…: Tb = 42.4°C.

- Species observed in the gaseous flux released at the dissolution of irradiated fuels,
- Species observed in the measurement of the efficiency of iodine traps,
- Species observed in the containment of a PWR in case of severe accidents,
- Species also observed in marine chemistry.



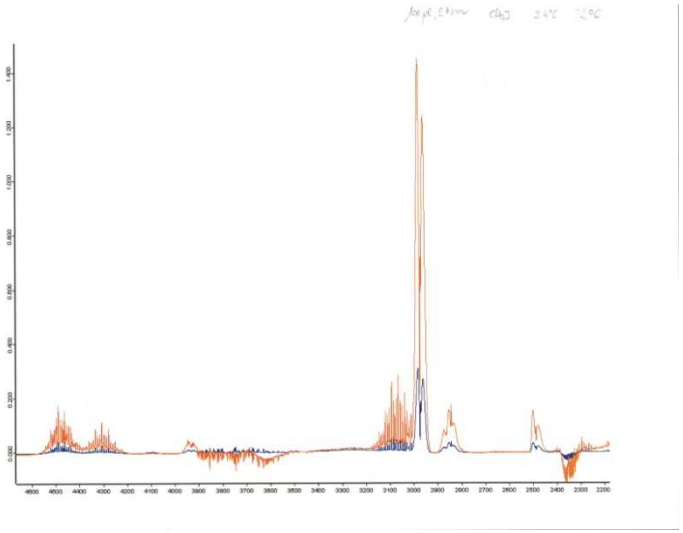
Simplified diagram of iodine transformations within the containment



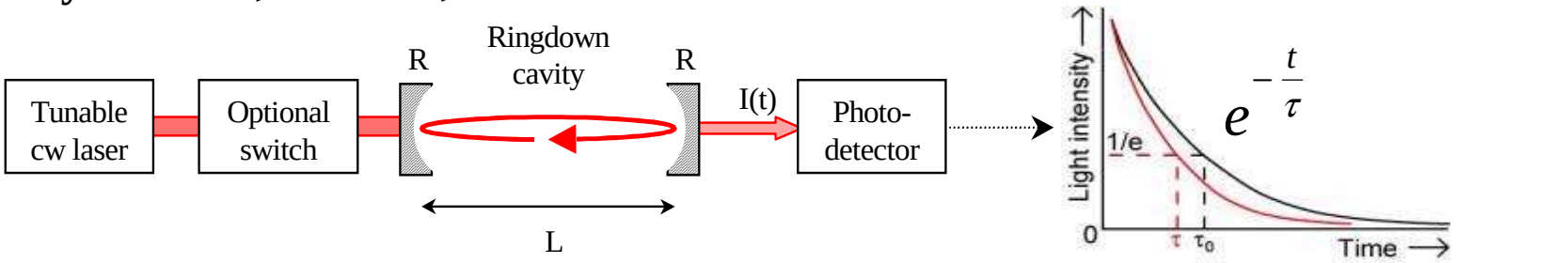
Amachi, S., Microbes Environ. Vol 23, n°4, 269-276 (2008)

Analytical techniques for organic iodine species determination

FTIR: mid IR range, LD<ppm.



CRDS (Cavity Ring Down Spectroscopy): Optical absorption technique very selective, sensitive, in the NIR.



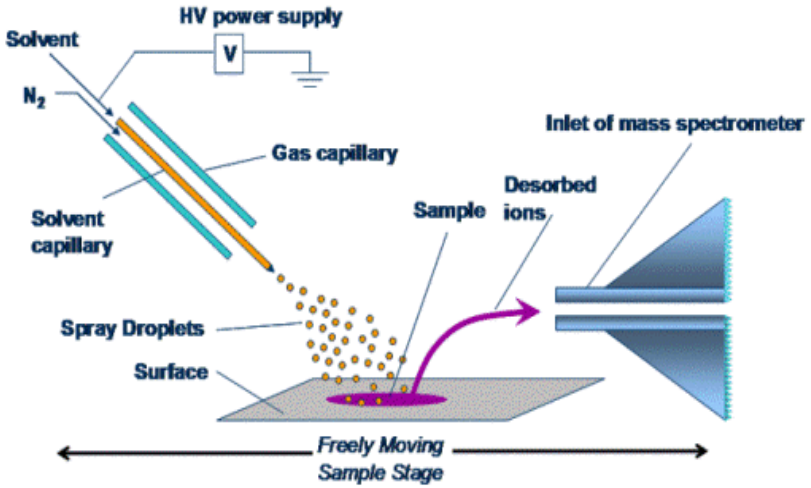
Optical cavity: L=1m ; $L_{optique}$ = 10 km
Theoretical DL ~ 10 ppb.

$$\alpha(\nu) = \frac{1}{c\ \tau(\nu)}$$

A. Pailloux, DPC/SECR/LRMO

Speciation of solid iodine and imaging.

Evaluation of DESI-TOF technique.
(Desorption – ionisation by electrospray coupled with a time of flight mass spectrometer).



Principle of DESI technique:

Application of an intense electric potentiel on capillaries containing the solvent and the vector gas.

- solvant nebulizing
- the droplets desorb the surface molecules

Advantages:

- Direct analyses on the sample without any preparation
- Soft ionization process which produces a lot of molecules and enables speciation studies.
- 2D imaging is possible.

D. Lebeau, DPC/SECR/LRMO

Examples of DESI-TOF potential for solid iodine speciation

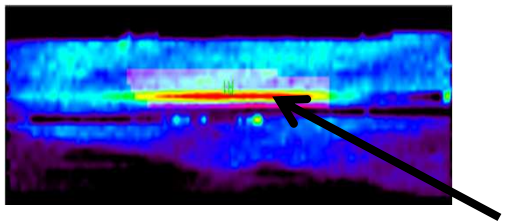
Application to waste storage

LCT XE Premier (Waters)
Source DESI 2D (Prosolia)

– Example: 4 mg d'EDTA on 10 g of concrete (400 ppm)

Image optique

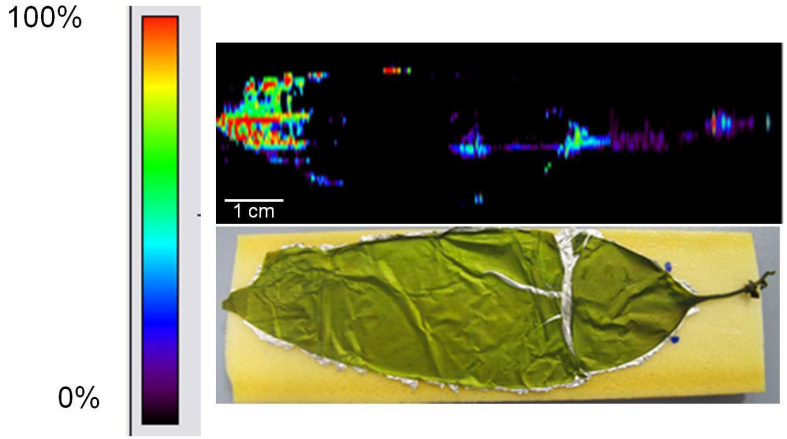
Image ionique
Ion m/z 344

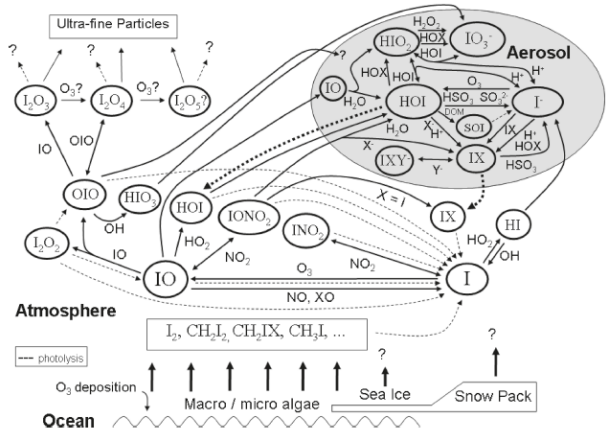


Localisation spécifique de l'ion [EDTA/Fe^{III}]

Application to marine chemistry

– Example: speciation and localization of iodine in *Laminaria digitata*





Examples of DESI-TOF potential for solid iodine speciation

Evaluation of the efficiency of iodine traps:

energie atomique • energies alternatives

Filters with activated charcoal (high specific surface) + KI + TEDA

Isotopic exchange:

$$K^{127}I + {}^{131}ICH3 \text{ ----- } K^{131}I + {}^{127}ICH_3$$

$$C_6H_{12}N_2 + ICH_3 \text{ ----- } C_8H_{18}N^{++} + 2I^-$$

In the case of severe accidents, comparative efficiency for I_2 and CH_3I

- **Influence of moisture**
- **Influence of temperature**
- **Influence of NOx**

Conclusions

energie atomique • energies alternatives

Iodine is a very important element in our life. It appears under numerous and various chemical species which offers an extensive chemistry according to the potential and the pH conditions.

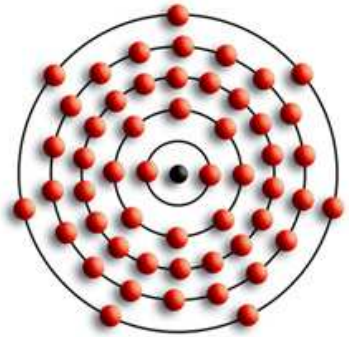
In the nuclear domain, it is a very important fission product especially in the gaseous phase, through the radioactivity of its isotopes.
Its detection at low level and its speciation are still the subject of numerous studies.

The continuous evolution of analytical tools enables speciation studies at traces level.

The knowledge of iodine speciation is not well known, particularly in the case of complex matrices.

Acknowledgments and additional bibliography

Acknowledgements to all contributors to iodine speciation knowledges.



State of the art report on iodine chemistry: B. Clement and al., NEA/CSNI/R(2007).

Commemorating two centuries of iodine research: an interdisciplinary overview of current research, F. C. Kupper and al., Angew. Chem. Int. Ed., 50, 11598- 11620.

Atmospheric chemistry of iodine, A. Saez-Lopez, Chem. Rev., under press.

The chemistry of iodine in containment, J.C. Wren, J.M. Ball, G. A. Glowa, nuclear technology, vol.129, (2000), 297.

Modelling of iodine radiochemistry in the ASTEC severe accident code:
Description and application to FPT-2 Phebus test, L. bosland, L. Cantrel, N. Girault, B. Clement, nuclear technology, vol 171, 88-107, (2010).

The geochemistry of iodine- a review, R. Fuge, C. C. Johnson, environmental geochemistry and health, 8(2), 31-54, (1986).