EDA Complexes of *N*-halosaccharins with N- and O-donor ligands†

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A series of EDA complexes of *N*-iodosaccharin (NISac) and *N*-bromosaccharin (NBSac) with nitrogen and oxygen electron-pair donors, NISac·H_2O, NISac·THF, NISac·Py, $NISac_2$·Pyz and $NBSac_2$·Pyz, was prepared and examined by X-ray diffraction and NMR. The complexes are relatively stable, crystalline compounds with the ligand bound to the halogen atom in a nearly linear arrangement N–halogen–ligand. The halogen–ligand distances are inversely proportional to the donor ability of the ligand. The interactions between ligand and halogen are stronger for iodine than bromine. The X-ray structure analysis has shown that for some compounds the N–X bond in the halosaccharin moiety is not coplanar with the isothiazole ring, and the quantum-chemical calculations demonstrate a high flexibility of the corresponding angle. Complexes were modelled also by DFT calculations using B3LYP and MPW1K functionals. A better fit of the computed geometry was obtained by the geometry optimization in a polar solvent continuum than in vacuum.

Introduction

Coordination compounds with halogen atoms in the form of halide anions as ligands or Lewis bases are very common, whereas those with halogens serving as Lewis acids are less known. Compounds of elemental halogens with aromatic hydrocarbons, ethers, amines and similar molecules were discovered early, and their structure elucidated in the 1960s by X-ray diffraction analysis.[1] In these adducts, one of the two halogen atoms of an X_2 molecule is linked to a donor atom or molecule (B), usually in a linear arrangement, *i.e.* the angle X–X···B is close to 180°. The adducts possess a dipole moment, even when formed from nonpolar molecules, indicating a substantial charge transfer from the ligand to halogen, hence the name charge transfer (CT) or electron-donor–acceptor (EDA) complexes. Since these early times, numerous studies of halogen and interhalogen complexes of this type appeared. Legon *et al.* studied such complexes with various donor molecules in the gas phase by fast spectroscopic methods.[2] He noticed a striking similarity between the properties of the bonding in halogen complexes of the type Y–X···B (Y = halogen or other electronegative atom or group) and analogous compounds with hydrogen, Y–H···B. By analogy with hydrogen bonding, a concept of "halogen bonding" was introduced. It covers a wide range of noncovalent interactions of more or less electropositive halogen atoms with Lewis bases, found in inorganic as well as in organic compounds. Its implications are found in supramolecular assemblies, biological systems, and other areas.[3,4]

N-Iodosaccharin, an efficient electrophilic iodinating agent, was found to crystallize with the incorporation of a water molecule.[5] Formation of crystals with water molecules of crystallization is widespread, even among organic compounds. Hydrates are often formed by compounds with acidic or basic oxygen and/or nitrogen functional groups, *e.g.* alcohols, acids, amino acids *etc.*, where water serves as a hydrogen bond donor, acceptor or both.[6] In the case of iodosaccharin, there are several potential sites to which water could bind: oxygen atoms of CO and SO_2 groups can serve as hydrogen-bond acceptors and, at the same time, the electropositive iodine atom as a halogen bond donor. X-Ray diffraction analysis clearly showed that water in NISac·H_2O is attached to the iodine atom. This finding and the fact that *N*-halosaccharins are useful electrophilic halogenating reagents[7] stimulated us to investigate the formation of *N*-iodo- and *N*-bromosaccharin complexes with several Lewis bases of differing electron-donor ability. Regioselectivity, demonstrated by *N*-bromosaccharin in bromination of polycyclic aromatic alcohols could be, at least to a certain degree, attributed to the formation of a complex of this type.[8]

In this paper, we present the preparation, crystal structures and theoretical investigations of structures of several *N*-bromo- and *N*-iodosaccharin complexes with nitrogen and oxygen ligands.

Results and discussion

Crystallization of *N*-iodosaccharin (NISac) in the presence of a Lewis base L results in a product, which contains NISac and L in 1 : 1 molar ratio (pyrazine is an exception, since the ratio is 2 : 1). The Lewis base can be a solvent itself (*e.g.* THF), or it can be added in a small excess relative to NISac. It is of interest to note that the recrystallization of crude iodosaccharin from

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† Electronic supplementary information (ESI) available: ORTEP drawings and structural parameters, computed geometries (Cartesian coordinates) and energies of NXSac·L complexes. CCDC reference numbers 746940–746945. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/b9nj00263d

THF–hexane or EtOAc–hexane mixtures yielded a compound, which upon filtering with suction and drying on the filter, contained *ca.* one equivalent of water, gained from "normally dry" solvents and/or air moisture.[5] The necessity of NISac to bind the electron donors is also illustrated by its insolubility in solvents lacking electron-donor ability (*e.g.* alkanes, dichloromethane). In an early attempt to isolate crystals of NISac·H_2O from moist THF–hexane, crystals of NISac·THF were obtained. These are not very stable and gradually lose THF. Likewise, the compound NISac·H_2O loses or gains water depending on air humidity.

X-Ray diffraction studies of NISac·THF and NISac·H_2O revealed that iodine is coordinated to the oxygen atom of the ligand. Stability of such complexes is expected to be proportional to the electron-donating ability of the ligand, and nitrogen ligands are anticipated to be better than oxygen ligands. In order to asses this, we also prepared related complexes with nitrogen ligands. Thus, addition of a small excess of pyridine to a solution of NISac in a mixture of MeOAc and heptane resulted in formation of a colourless crystalline precipitate, NISac·Py. In a similar fashion, complexes $NISac_2$·Pyz, $NBSac_2$·Pyz and some others were obtained. These complexes are more stable, at least when compared to those with oxygen ligands, and can be handled at room temperature and atmosphere.

An attempt to evaluate the stability of complexes in solution was made. First, we tried to make these measurements by the use of UV spectroscopy.[9] Addition of amines to acetonitrile solutions of *N*-halosaccharins resulted in the formation of new absorption bands in the range of 250–300 nm, *i.e.* in the region, where the bands of *N*-halosaccharins and hetero-aromatic amines also appear. Due to a substantial band overlap, UV spectroscopy was not found suitable for the study of these compounds. More insight into the behaviour of complexes in solution was offered by NMR.

A solution of NISac·Py in acetonitrile-d_3 exhibits at room temperature or below a set of broad peaks which become sharp at −40 °C. Addition of pyridine to this solution at −40 °C results in the appearance of an additional set of signals corresponding to free pyridine. From this, it can be inferred that no or very little free pyridine can be found in the solution of the complex. The acetonitrile-d_3 solution of NISac·THF exhibits, besides NISac, only peaks of free THF. Addition of THF to the NMR tube did not affect the chemical shift of THF resonances; only an increase in integrals was observed. In the spectrum of NBSac·Py in acetonitrile-d_3, a set of sharp peaks appears, which is shifted upfield upon addition of pyridine, and no additional peaks appeared, even at −40 °C. These results show that the stability of the NISac·Py complex is substantial. The complex shows very little dissociation at millimolar concentrations in acetonitrile, while NISac·THF is completely dissociated. Though THF is a weaker ligand than pyridine the reason for the complete dissociation probably lies in a competition between THF and the solvent, acetonitrile, as ligand. The degree of dissociation of NBSac·Py cannot be determined, since even at −40 °C, a fast exchange is taking place. Faster exchange for NBSac·Py compared to the analogous NISac·Py probably indicates a weaker halogen-to-ligand bond in the bromine compound.

Solid-state structures

Since not all the *N*-halosaccharin complexes formed crystals suitable for the X-ray diffraction analysis, measurements could not performed on all the compounds (Table 1). Crystals of *N*-bromosaccharin were also subjected to crystallographic analysis (*N*-iodosaccharin, which is insoluble in apolar solvents did not provide crystals, not containing solvent molecules of crystallization). The donor atom of the ligand L is bound to a halogen with a nearly linear arrangement of N, X and the donor atom of the ligand in all complexes (Fig. 1). The corresponding angles are in the range 174.5(4)–178.51(9)°. The N–I and I···L bond lengths are interdependent: as the I···L distance decreases, the N–I bond in the *N*-iodosaccharin molecule increases in a regular manner (Table 1). All the observed X···L distances are significantly shorter than the sums of the corresponding van der Waals radii which are 3.50 Å for I + O, 3.53 Å for I + N, and 3.40 Å for Br + N.[10]

The strongest interaction occurs in the *N*-iodosaccharin complex with pyridine, NISac·Py, which displays by far the shortest iodine–ligand distance, 2.279(11) Å. Moreover, this distance is of comparable length to the N–I bond length in the *N*-iodosaccharin moiety of the complex. Pyrazine, another nitrogen donor ligand, acts as a somewhat weaker donor, in accordance with its lower basicity. The weakening may also be attributed to the fact that pyrazine functions as a bidentate ligand. Its binding to two acceptors, two iodine atoms of two *N*-iodosaccharin molecules (Fig. 2), results in the reduction of electron density on both nitrogen atoms. The complexes with the oxygen donor ligands, NISac·H_2O and NISac·THF, display even longer I···L distances. In contrary to our expectations, the I···O bond in the water complex is shorter than in the THF complex despite the fact that THF is considered to be a better electron donor than water. The donor numbers of THF and water are 20.0 and 18.0 kcal mol^{-1}, respectively.[11]

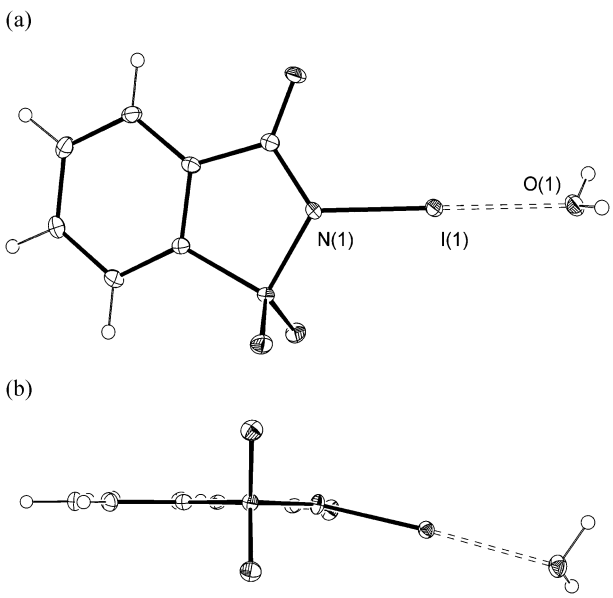


Fig. 1 (a) An ORTEP drawing of NISac·H_2O with thermal ellipsoids drawn at the 30% probability level. (b) A projection of the NISac·H_2O complex along the aromatic plane showing the deviation of the iodine atom from this plane.

Table 1 Selected bond lengths (Å) and angles (°) in NISac and NBSac complexes[a]

Compd	N–X[b]	X···L	N–X···L	C(6)–C(7)–N–X[c]
NISac·H_2O	2.096(2)	2.443(2)	177.68(7)	167.4(1)
NISac·THF	2.073(2)	2.512(2)	178.51(9)	180.0
NISac·Py	2.254(11)	2.279(11)	174.5(4)	164.6(9)
$NISac_2$·Pyz	2.142(2)	2.423(2)	175.26(6)	170.8(1)
$NBSac_2$·Pyz	1.906(1)	2.410(1)	175.22(6)	179.5(1)
NBSac[d]	1.847(2), 1.835(3)	—[e]	—[e]	166.1(2), 178.9(2)

[a] Structural parameters of *N*-bromosaccharin are given for comparison. [b] X = I or Br. [c] See the atom labelling scheme. The torsion angle serves as a rough measure of the non-planarity of the *N*-halosaccharin moiety. [d] Two sets of parameters, one for each molecule in the asymmetric unit. [e] Intermolecular interactions in NBSac involving the bromine atom are described in the text.

Gas-phase studies of halogen or interhalogen complexes with oxygen donors have also shown the X···O distances to be shorter for those with ethers than for those with water.[2b] On the other hand, the solid-state structures of coordination compounds of transition metals with water or THF display no obvious trend.[12] The longer I···O bond in the NISac·THF complex could find its origin in steric effects in the crystal lattice which prevent a closer approach of THF and *N*-iodosaccharin molecules. The quantum-chemical calculations on isolated complexes also predict a shorter bond for the complex with THF (Table 2).

N-Halosaccharin complexes with pyrazine, $NISac_2$·Pyz and $NBSac_2$·Pyz, display very similar X···L distances. By taking into account the van der Waals radii of iodine and bromine, the bond in the *N*-bromosaccharin complex should be shorter. This clearly indicates that the interaction of bromine with the ligand is weaker as compared to that of iodine.

The difference can be rationalized by the higher electropositive nature of iodine as compared to that of bromine, when bound to an electron-withdrawing group. The charges on halogen atoms in NXSac, as calculated by NBO analysis, are 0.325 and 0.438 a.u. for bromine and iodine, respectively.[13] A similar trend was observed previously for *N*-bromosuccinimide (NBS) and *N*-iodosuccinimide (NIS). In the absence of a suitable electron donor ligand, the halogen participates in short interactions with the carbonyl oxygen atom of the adjacent molecule. These intermolecular interactions are shorter for the iodine than for the bromine compound, 2.580(6) *vs.* 2.802(7) Å, respectively.[14,15] In a similar manner, bromine in *N*-bromosaccharin is involved in intermolecular interactions with the carbonyl [2.727(2) and 2.853(2) Å] or the sulfone [3.276(3) Å] oxygen atoms. Consequently, *N*-bromosaccharin molecules are linked through the agency of Br···O interactions into infinite chains (Fig. S7, ESI†). It should be noted that this type of interactions have been observed previously.[16]

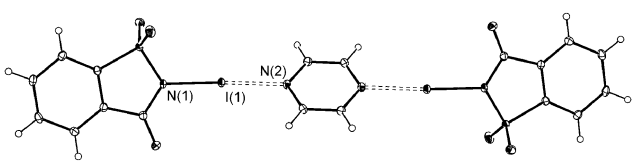


Fig. 2 An ORTEP drawing of $NISac_2$·Pyz with thermal ellipsoids drawn at the 30% probability level. Both the $NISac_2$·Pyz and $NBSac_2$·Pyz adducts have crystallographically imposed inversion symmetry with the centre of gravity of pyrazine molecule at the inversion centre.

Table 2 Measured and computed X···L and N–X bond lengths and energies in EDA complexes of NISac and NBSac[a]

Compound	Method[b]	*d*(X···L)/Å	*d*(N–X)/Å	$-\Delta H_f^c$/kJ mol^{-1}
NISac·Py	X	2.279	2.254	—
NISac·Py	B	2.551	2.142	49.9
NISac·Py	M	2.499	2.103	53.5
NISac·Py	MP2	2.602	2.125	—
NISac·Py	M (soln)[d]	2.307	2.232	—
$NISac_2$·Pyz	X	2.423	2.142	—
$NISac_2$·Pyz	M	2.649	2.068	67.5[e]
NISac·H_2O	X	2.443	2.096	—
NISac·H_2O	M	2.713	2.051	25.3
NISac·THF	X	2.512	2.073	—
NISac·THF	M	2.588	2.063	33.2
NISac	M	—	2.029	—
$NBSac_2$·Pyz	X	2.410	1.906	—
$NBSac_2$·Pyz	M	2.470	1.915	56.8[e]
NBSac	X	—	1.835, 1.847	—
NBSac	M	—	1.864	—

[a] Enthalpies of formation calculated from total enthalpies, B3LYP or MPW1K/6-311+G** in vacuum. [b] X = X-ray diffraction; B = B3LYP; M = MPW1K. [c] Enthalpy of the reaction NXSac·L → NXSac + L. [d] Geometry optimized in DMSO solution. [e] Enthalpy of the reaction $NXSac_2$·L → 2NXSac + L.

The X-ray structural data on the EDA complexes involving halogens and Lewis bases are rather scarce. A prominent example is a 2 : 1 complex between NBS and a strong base, 1,4-diazabicyclo[2.2.2]octane.[17] In spite of the bidentate binding of the base, the complex features a significantly shorter Br···L distance than $NBSac_2$·Pyz, 2.332(4) *vs.* 2.410(1) Å, respectively. Another example is a complex of NIS with imine in which the distance between iodine and the imine nitrogen is 2.486 Å.[18]

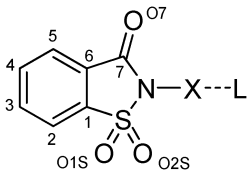
The comparison of our data with published distances for related halogen or interhalogen complexes[1] reveals that the I···O bonds in NISac·H_2O and NISac·THF are shorter than the corresponding bond in ICl·dioxane (2.57 Å). This would suggest a stronger interaction and a higher polarization of the N–I bond in NISac than the Cl–I bond. Indeed, atomic charges on iodine, determined by NBO analysis (see below) are 0.438 and 0.247 a.u. in NISac and ICl, respectively. Such a polarization makes iodine highly electrophilic and, consequently NISac is a good iodination reagent.

DFT calculations on the B3LYP or MPW1K/6-311+G** level (LACV3P pseudopotential applied for bromine and iodine) yielded halogen–donor atom distances, as a rule, longer than observed by X-ray crystallography (Table 2, a more comprehensive table of calculated values can be found in

ESI, Table S3†). At the same time, the computed N–I (or Br) bond lengths in the halosaccharin moiety are generally shorter. A stronger interaction of *N*-halosaccharin with a ligand would cause a shortening of the I···L bond whereas the N–I bond would lengthen. These results suggest that the interaction energy, computed on the isolated complex, is underestimated. In the complex, there is a substantial charge transfer between the acceptor and the donor molecule. Further interactions of the complex with polar medium would stabilize such a dipolar structure. The crystal lattice provides an environment with many intermolecular interactions, whereas the calculation is performed on the isolated complex. An improvement can be expected if the calculations are carried out taking into account such interactions, *e.g.* solvation with a polar solvent. The bond lengths for the complexes calculated in DMSO using a continuum solvation model (Poisson—Boltzmann), indeed resemble more closely the values found in crystals (Table 2). DMSO was chosen arbitrarily as a typical polar solvent. The enthalpies of formation for the complexes in solution are not amenable to calculation due to extremely long computation times. The charge transferred between NISac and pyridine in the complex increases from 0.134 to 0.253 a.u. from vacuum to DMSO, respectively, as determined by the NBO approach (MPW1K geometry).

A comparison of the measured and computed bond lengths by the two methods shows that MPW1K yields better values for the I···L bonds than the more widely used B3LYP. Average deviations are 0.14 and 0.21 Å for MPW1K and B3LYP, respectively. For other bonds, both functionals behave similarly. The MPW1K functional was originally developed for chemical kinetics calculations, *i.e.* the computation of the transition state structures with weak and elongated bonds.[19] Similar situations can be found in coordination compounds where the MPW1K functional has already found applications.[20] It has also proved to be more accurate than B3LYP in CT complexes.[21] Calculation at the MP2 level does not result in significant improvement in the calculated distances.

The deviation of the *N*-halosaccharin molecule from planarity is another structural feature which deserves to be commented upon. In some complexes, NISac·H_2O, NISac·Py and $NISac_2$·Pyz, the N–X bond vector is not coplanar with the isothiazole ring (Fig. 1). A convenient way to measure this deviation is by the torsion angle between the C(6)–C(7), C(7)–N and N–X bonds (Scheme 1). The latter occupies the range 164.6(9)–170.8(1)° in the case of "non-planar" compounds. Although the largest deviation is observed for the pyridine complex, there is no straightforward correlation between the halogen–ligand bond length and the planarity of the *N*-halosaccharin moiety of the complex. For instance, NISac·H_2O and NISac·THF complexes, which display rather similar bonding patterns differ drastically in the torsion angle. While the THF complex is planar, the complex with water is not. The structure of *N*-bromosaccharin itself provides yet another example: of the two crystallographically distinct molecules in the asymmetric unit, one is planar and the other is not. Again, the pair do not differ significantly either in the bonding pattern or in the intermolecular interactions. Calculation of ΔH_f(NXSac) *vs.* the torsion angle shows that



Scheme 1 The atom numbering scheme used for the NXSac·L complexes.

the angle is very flexible and that the molecule easily accommodates to the environment in the crystal lattice (Fig. 3). An angle deformation of 15° results only in *ca.* 2 kJ mol^{-1} increase in energy. Calculation made on a model complex NISac·NH_3 yielded very similar values: the flexibility of this angle is virtually unaffected by binding of the ligand.

Experimental

General

NMR spectra were measured on Bruker Avance 300 DPX (300 MHz) spectrometer. IR spectra were measured on Nujol mulls or directly on solid samples using Golden Gate ATR with a Perkin Elmer Spectrum 100 spectrometer. Elemental analyses were performed at the Elemental Analyses Centre at the University of Ljubljana.

Synthesis

N-Bromosaccharin[22] and *N*-iodosaccharin[5] were prepared by literature procedures. Yields of complexes are in most cases nearly quantitative, however in the procedures described below, the goal was the preparation of single crystals for X-ray diffraction analysis and the yields were correspondingly lower (and are not reported).

Preparation of NISac·H_2O[5]. 0.05 mmol of *N*-iodosaccharin was dissolved in 1 mL of MeCN and diluted with 2 mL of water. The mixture was then allowed to evaporate slowly in a refrigerator. IR absorptions, ν_{max}/cm^{-1} 3514 and 3453 (OH), 1722 and 1704 (CO).

Preparation of NISac·THF. 0.1 mmol of *N*-iodosaccharin was dissolved in 1 mL of THF, diluted with 2 mL of heptane

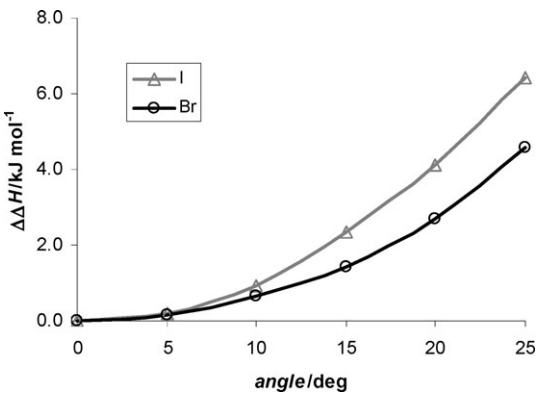


Fig. 3 Computed ΔH_f of *N*-bromo- and *N*-iodosaccharin *vs.* angle deformation (defined as 180° − |torsion angle C(6)–C(7)–N–X|) [B3LYP/6-311G**].

Table 3 Crystallographic data

	NISac·H_2O	NISac·THF	NISac·Py	$NISac_2$·Pyz	$NBSac_2$·Pyz	NBSac
Empirical formula	$C_7H_6INO_4S$	$C_{11}H_{12}INO_4S$	$C_{12}H_9IN_2O_3S$	$C_{18}H_{12}I_2N_4O_6S_2$	$C_{18}H_{12}Br_2N_4O_6S_2$	$C_7H_4BrNO_3S$
Formula weight	327.09	381.18	388.17	698.24	604.26	262.08
Crystal system	Monoclinic	Orthorhombic	Monoclinic	Monoclinic	Monoclinic	Monoclinic
Space group	$P2_1/n$	*Pmnb*	$P2_1/a$	$P2_1/n$	$P2_1/n$	$P2_1/a$
T/K	150(2)	150(2)	293(2)	150(2)	150(2)	293(2)
a/Å	8.4574(2)	8.24280(10)	12.6184(3)	9.1283(3)	7.78470(10)	7.7944(2)
b/Å	9.0194(2)	9.14280(10)	7.8019(2)	8.1398(2)	9.8956(2)	28.4335(7)
c/Å	12.9095(3)	17.6493(3)	14.8718(4)	14.4767(4)	14.0214(2)	8.6973(2)
β/°	90.2461(14)	90	113.6530(12)	90.810(2)	96.2877(10)	116.1549(12)
V/Å^3	984.74(4)	1330.09(13)	1341.10(6)	1075.55(5)	1073.63(3)	1730.15(8)
D_c/g cm^{-3}	2.206	1.904	1.923	2.156	1.869	2.012
Z	4	4	4	2	2	8
λ/Å	0.71073	0.71073	0.71073	0.71073	0.71073	0.71073
μ/mm^{-1}	3.451	2.570	2.548	3.163	4.015	4.962
Collected reflections	4319	2880	5589	4685	4719	7652
Unique reflections	2239	1605	3044	2449	2449	3955
R_{int}	0.0138	0.0093	0.0207	0.0114	0.0105	0.0218
Observed reflections	2025	1534	2829	2279	2313	3070
$R1^a$ ($I > 2\sigma(I)$)	0.0187	0.0212	0.0879	0.0182	0.0212	0.0315
$wR2^b$ (all data)	0.0466	0.0528	0.2702	0.0443	0.0557	0.0795

^{a} $R1 = \sum||F_o| - |F_c||/\sum|F_o|$. ^{b} $wR2 = \{\sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]\}^{1/2}$.

and left to stand in a refrigerator. IR absorptions, ν_{max}/cm^{-1} 3071 and 2879 (CH), 1715 (CO). Elemental analysis. Found C 34.6, H 3.0, N 3.7. Calc. for $C_{11}H_{12}INO_4S$: C 34.7, H 3.2, N 3.7%.

Preparation of complexes with pyridine and pyrazine. Typically, 0.05 mmol of *N*-halosaccharin was dissolved in 1 mL of the appropriate solvent (CH_2Cl_2, MeOAc) and 0.2 mmol of amine was added. To this solution, 1–2 mL of a higher boiling solvent was added, in which the solubility of *N*-halosaccharin is low (*e.g.* heptane, CCl_4). The mixture was then allowed to evaporate slowly in a refrigerator.

NISac·Py. IR absorption, ν_{max}/cm^{-1} 1690 (CO). Elemental analysis. Found C 37.3, H 2.3, N 7.2. Calc. for $C_{12}H_9IN_2O_3S$: C 37.1, H 2.3, N 7.2%.

$NISac_2$·Pyz. IR absorptions, ν_{max}/cm^{-1} 1720 and 1709 (CO). Elemental analysis. Found C 31.1, H 1.8, N 8.0. Calc. for $C_{18}H_{12}I_2N_4O_6S_2$: C 31.0, H 1.7, N 8.0%.

$NBSac_2$·Pyz. IR absorption, ν_{max}/cm^{-1} 1722 (CO). Elemental analysis. Found C 36.0, H 2.0, N 9.3. Calc. for $C_{18}H_{12}Br_2N_4O_6S_2$: C 35.8, H 2.0, N 9.3%.

X-Ray crystal structure determinations

The crystals used were mounted on the tip of glass fibres with a small amount of silicon grease and transferred to a goniometer head. Data were collected on a Nonius Kappa CCD diffractometer using graphite-monochromated Mo-Kα radiation. Data reduction and integration were performed with the software package DENZO-SMN.[23] Averaging of the symmetry-equivalent reflections largely compensated for the absorption effects. The coordinates of some or all of the non-hydrogen atoms were found *via* direct methods using the structure solution program SHELXS.[24] The positions of the remaining non-hydrogen atoms were located by use of a combination of least-squares refinement and difference Fourier maps in the SHELXL-97 program.[24] Positions of water hydrogen atoms in NISac·H_2O were located from the residual electron density map. All other hydrogen atoms were included in the structure factor calculations at idealized positions. The modest quality of the crystal of NISac·Py resulted in large $R1$ and $wR2$ residuals. Furthermore, large residual electron density was found in the final difference electron density maps. The two maxima are 5.27 (0.95 Å from iodine atom) and 2.37 e Å^{-3} (1.42 Å from the pyrazine *ortho*-hydrogen atom). Repeated attempts to obtain crystals with better diffraction data have not been successful. For NISac·THF, the *Pmnb* space group (a non-standard setting of *Pnma*) was chosen.

All the calculations were performed using the WinGX programme suite.[25] Figures depicting the structures were prepared by ORTEP3,[26] SHELXTL,[27] and Mercury.[28] Cell parameters and refinement results are summarized in Table 3.

Computational details

All structures were completely optimized at the MPW1K or B3LYP/6-311 + G** level, using LACV3P pseudopotential for Br and I. In MP2 calculation, localized MP2 level of theory with Pipek–Mezey valence localization method was applied. All computations were run on *Jaguar*, version 6.5; Schrodinger, LLC: Portland, OR, 2005.

Conclusion

N-Iodo- and *N*-bromosaccharins form relatively stable EDA complexes with oxygen and particularly with nitrogen electron-pair donors. X-Ray diffraction studies show that the ligand is bound to the halogen atom in an almost linear arrangement of N, X and the donor atom of the ligand. The distance X···L is inversely proportional to the ligand donor ability and increases in the order: Py, Pyz, water and THF. The X···L interaction in iodosaccharin complexes is stronger than in the bromosaccharin analogues, which points to a higher stability of the former. Solution studies of complexes by NMR exhibit a similar picture. The N–X bond

of halosaccharin in some crystals is not coplanar with the isothiazole ring. Quantum-chemical calculations demonstrate that the angle between the N–X bond and the ring is very flexible and that the molecule easily accommodates to the conditions in the crystal lattice. Comparison of the two DFT functionals show that the calculations carried out by the MPW1K functional better describe the X···L and N–X bonds than the popular B3LYP. An additional improvement in calculations is the geometry optimization in a continuum solvent model, *i.e.* a medium which better resembles the conditions in a crystal than the vacuum does.

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References and notes

1 O. Hassel and C. Rømming, *Q. Rev. Chem. Soc.*, 1962, **16**, 1–18, and references therein.
2 (*a*) A. C. Legon, *Chem.–Eur. J.*, 1998, **4**, 1890–1897; (*b*) A. C. Legon, *Angew. Chem., Int. Ed.*, 1999, **38**, 2686–2714.
3 P. Metrangolo, G. Resnati, T. Pilati and S. Biella, *Struct. Bonding*, 2008, **126**, 105–136.
4 P. Metrangolo, F. Meyer, T. Pilati, G. Resnati and G. Terraneo, *Angew. Chem., Int. Ed.*, 2008, **47**, 6114–6127; H. L. Nguyen, P. N. Horton, M. B. Hursthouse, A. C. Legon and D. W. Bruce, *J. Am. Chem. Soc.*, 2004, **126**, 16–17; J. Xu, X. Liu, J. K-P. Ng, T. Lin and C. He, *J. Mater. Chem.*, 2006, **16**, 3540–3545; M. Fourmigué and R. P. Batail, *Chem. Rev.*, 2004, **104**, 5379–5418; P. K. Thallapally, G. R. Desiraju, M. Bagieu-Beucher, R. Masse, C. Bourgogne and J. F. Nicoud, *Chem. Commun.*, 2002, 1052–1053; P. Auffinger, F. A. Hays, E. Westhof and P. S. Ho, *Proc. Natl. Acad. Sci. U. S. A.*, 2004, **101**, 16789–16794; P. Metrangolo and G. Resnati, *Science*, 2008, **321**, 918–919; M. Iwaoka, H. Komatsu, T. Katsuda and S. Tomoda, *J. Am. Chem. Soc.*, 2002, **124**, 1902–1909.
5 D. Dolenc, *Synlett*, 2000, 544–546.
6 F. H. Allen, *Acta Crystallogr., Sect. B: Struct. Sci.*, 2002, **58**, 380–388.
7 K. I. Booker-Milburn, D. J. Guly, B. Cox and P. A. Procopiou, *Org. Lett.*, 2003, **5**, 3313–3315; S. P. L. de Souza, J. F. M. da Silva and M. C. S. de Mattos, *Synth. Commun.*, 2003, **33**, 935–939; H. Firouzabadi, N. Iranpoor and F. Ebrahimzadeh, *Tetrahedron Lett.*, 2006, **47**, 1771–1775; P. K. Mandal and A. K. Misra, *Synlett*, 2007, 1207–1210; M. Aloui and A. J. Fairbanks, *Chem. Commun.*, 2001, 1406–1407; D. Dolenc, *Synth. Commun.*, 2003, **33**, 2917–2924; D. Urankar, I. Rutar, B. Modec and D. Dolenc, *Eur. J. Org. Chem.*, 2005, 2349–2353.
8 B. Zajc, *J. Org. Chem.*, 1999, **64**, 1902–1907.
9 H. A. Benesi and J. H. Hildebrand, *J. Am. Chem. Soc.*, 1948, **70**, 2832–2833; H. A. Benesi and J. H. Hildebrand, *J. Am. Chem. Soc.*, 1949, **71**, 2703–2707.
10 Data were taken from B. Douglas, D. McDaniel and J. Alexander, *Concepts and Models of Inorganic Chemistry*, John Wiley & Sons, Inc., New York, 3rd edn, 1994, p. 102.
11 V. Gutmann and R. Schmid, *Coord. Chem. Rev.*, 1974, **12**, 263–293.
12 For instance, similar Cr–O(water or THF) distances were observed for a series of octahedral Cr(III) complexes: 1.994(4)–2.077(4) Å for $CrCl_3(THF)_3$ (F. A. Cotton, S. A. Duraj, G. L. Powell and W. J. Roth, *Inorg. Chim. Acta*, 1986, **113**, 81–85), and 2.006(9)–2.016(9) Å for $CrCl_3(H_2O)$(methylnicotinate)$_2$ (J. V. McArdle, E. de Laubenfels, A. L. Shorter and H. A. Ammon, *Polyhedron*, 1982, **1**, 471–474).
13 B3LYP/6-311G** on isolated molecule. NBO 5.0.: E. D. Glendening, J. K. Badenhoop, A. E. Reed, J. E. Carpenter, J. A. Bohmann, C. M. Morales and F. Weinhold, *Theoretical Chemistry Institute*, University of Wisconsin, Madison, WI, 2001.
14 O. Jabay, H. Pritzkow and J. Jander, *Z. Naturforsch., Teil B*, 1977, **32**, 1416–1420.
15 K. Padmanabhan, I. C. Paul and D. Y. Curtin, *Acta Crystallogr., Sect. C: Cryst. Struct. Commun.*, 1990, **46**, 88–92.
16 J. Leser and D. Rabinovich, *Acta Crystallogr., Sect. B: Struct. Crystallogr. Cryst. Chem.*, 1978, **34**, 2250–2280; P. Murray-Rust and W. D. S. Motherwell, *J. Am. Chem. Soc.*, 1979, **101**, 4374; A. Waterfeld, W. Isenberg, R. Mews, W. Clegg and G. M. Sheldrick, *Chem. Ber.*, 1983, **116**, 724–731.
17 E. H. Crowston, A. M. Lobo, S. Prabhakar, H. S. Rzepa and D. J. Williams, *J. Chem. Soc., Chem. Commun.*, 1984, 276–278.
18 I. Castellote, M. Moron, C. Burgos, J. Alvarez-Builla, A. Martin, P. Gomez-Sal and J. J. Vaquero, *Chem. Commun.*, 2007, 1281–1283.
19 B. J. Lynch, P. L. Fast, M. Harris and D. G. Truhlar, *J. Phys. Chem. A*, 2000, **104**, 4811–4815.
20 B. Modec, D. Dolenc and M. Kasunič, *Inorg. Chem.*, 2008, **47**, 3625–3633.
21 Y. Zhao and D. G. Truhlar, *J. Chem. Theory Comput.*, 2005, **1**, 415–432.
22 B. Zajc, *Synth. Commun.*, 1999, **29**, 1779–1784.
23 Z. Otwinowski and W. Minor, *Methods Enzymol.*, 1997, **276**, 307–326.
24 G. M. Sheldrick, *SHELX-97, Programs for Crystal Structure Analysis*, University of Göttingen, 1997.
25 L. J. Farrugia, *J. Appl. Crystallogr.*, 1999, **32**, 837–838.
26 L. J. Farrugia, *J. Appl. Crystallogr.*, 1997, **30**, 565.
27 *SHELXTL version 6.12. Software Package for Crystal Structure Determination*, Bruker Analytical X-ray Systems, Inc., Madison, WI, 2000.
28 C. F. Macrae, P. R. Edgington, P. McCabe, E. Pidcock, G. P. Shields, R. Taylor, M. Towler and J. van de Streek, *J. Appl. Crystallogr.*, 2006, **39**, 453–457.