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Open questions on toxic heavy metals Cd, Hg and Pb binding small components of DNA and nucleobases. Are there any predictable trends?

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Supporting Information
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Bibliographic compilation of experimental and theoretical work on Cd, Hg and Pb.

Cd

Cadmium is categorized as a non-essential element since it is not naturally involved in any physiological process. However, although its ionic radius is larger (~0.18 Å), it is chemically similar to zinc and often replaces it in binding sites of enzymes and proteins. The binding of Cd to proteins is therefore one of the reasons for its toxicity**,** thereby inhibiting important physiological functions.[1, 2] This is the case for example of zinc finger proteins which are involved in DNA repair. Zinc finger proteins are characterized by Zn^{2+} ions interacting preferentially with cysteine (Cys) and histidine (His) residues, and the particularly high affinity of toxic metals such as Cd for thiol groups, make cysteine-containing zinc finger proteins particularly susceptible to Zn^{2+} replacement. Zn replacement by Cd inactivates these proteins, which can no longer bind to DNA.[3] Exposure to cadmium also promotes the synthesis of metallothioneins (MT)[4], which are a class of cysteine-rich proteins playing a role in the protection against metal toxicity and oxidative stress, and which have the capability to bind cadmium through their Cys residues.[5, 6]

The importance of the substitution of Zn by Cd in proteins has therefore motivated numerous experimental and/or theoretical studies about the interactions of cadmium with amino acids, proteins and relevant model compounds. Performing these studies in the gas phase allows the description of these interactions at the molecular level and can give access to the intrinsic properties of such interactions in the absence of solvation and counter-ion effects. Those that have been carried out during the three last decades, are briefly summarized in this section.

Given the key role played by the cysteine residue, a peculiar attention was given to the interactions between cadmium and this amino acid. In 2005, Belcastro and co-workers[7] published a detailed computational study about the doubly-charged M^{2+}-cysteine complex (M=Cu, Zn, Cd , Hg). To this end, calculations were carried out in the framework of density functional theory (DFT), and different binding schemes were considered, including both neutral and zwitterionic forms, the latter being often strongly stabilized when complexed with metal ions. Their study showed that Zn^{2+} and Cd^{2+} ions share the same preferred binding scheme, characterized by a tridentate interaction involving the carbonyl oxygen, nitrogen and sulfur atoms of neutral cysteine. It is similar

to that found both experimentally and theoretically for Li^+ and Na^+,[8, 9] whereas different types of complexes coexist for heavier alkali metals.[9] On the other hand, this binding scheme turned to be different than that computed for Cu^{2+} and Hg^{2+}, which implied a zwitterionic form of cysteine. Note that a more recent DFT study using a larger basis set than LANL2DZ, also found for Cd^{2+} a global minimum involving zwitterionic cysteine, characterized by a bidentate interaction with the carbonyl oxygen and the deprotonated thiol group.[10] This discrepancy was attributed to the larger basis set superposition error associated with the LANL2DZ.

When studying the gas-phase interactions between transition metals and aminoacids by mass spectrometry, both the type and the stoichiometry of the complexes observed experimentally may strongly depend on the type of salts used to prepare the solutions, but also on the ionization source used. But generally, when using electrospray ionization (ESI), the interactions taking place with dications are associated with deprotonation of the amino acid. This had been shown twenty years ago for example for Zn^{2+} ions by the group of Ohanessian with glycine, asparagine or aspartic acid.[11-13]. Later, Burford and co-workers[14] studied the complexes generated by electrospray between a series of toxic metal ions (and notably cadmium and mercury), with the whole series of aminoacids (aa). The observed spectra were found independent of the reaction mixture stoichiometry (10:1 – 1:10). Starting from nitrate salts, they observed deprotonated amino acids complexes with Hg^{2+} and Cd^{2+}. Remarkably, with cadmium, complexes of general formula $[Cd(aa)+X]^+$ ($X=NO_3^-$), that is formally involving an intact amino acid, were observed with all the amino acids but histidine and asparagine. Similar complexes involving neutral aminoacids can also be generated starting from chloride salts ($X=Cl^-$), as shown by the studies carried out by the group of P. B Armentrout (*vide infra*).[15-25] Burford and co-workers also examined the interactions taking place with the tripeptide glutathione (GSH: γ-Glu–Cys–Gly).[26] With Cd, a very intense $[Cd(GSH)-H]^+$ complex is observed. Interestingly, the MS/MS spectrum of this complex shows only product ions retaining the thiolate group, indicative of the strong affinity of cadmium for thiolates. Ternary equimolar mixtures of $Cd(NO_3)_2$ and two biologically relevant thiol amino acids R_1SH and R_2SH have been also studied by ESI-MS.[27] Again, deprotonation occurred and complexes of the type $[Cd(R_1SH)(R_2SH),-H]^+$ were generated by electrospray. Interestingly, the theoretical 1:2:1 intensity ratio expected for homodimers and heterodimers was not observed, suggesting some degree of discrimination between the

different thiols. Authors also noticed that the intensities of the complexes were much less intense than those obtained with Hg^{2+} under similar conditions[28], pointing to a higher affinity of mercury for thiolates.

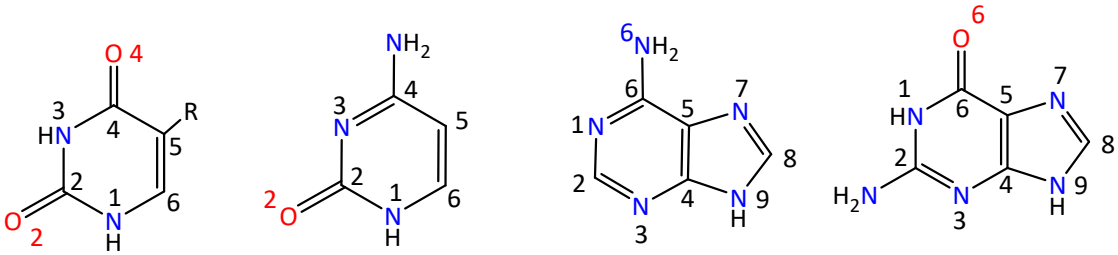
In these two previous experimental studies dealing with Cd^{2+} interactions, authors assumed an interaction with deprotonated sulfur to interpret their MS/MS spectra. Furthermore, Rubino and co-workers suggested for their dimers a linear S-Cd-S geometry. The first assumption sounds reasonable according to several theoretical reports on model compounds. For instance, a study published in 2000 by Rulíšek and Havlas, in which side chains of amino acids were replaced by functional groups, showed that the interaction energies of negatively charged residues (deprotonated amino acid side chains) were by one order of magnitude greater than those of the neutral species.[29] This theoretical study gives also support to the second assumption, as linear coordination geometry turned to be especially favorable for soft metal ions such as Cd(II) and Hg(II). A theoretical study about the interactions between group 12 metal $M_n(H_2O)^{2+}$ (n=0-2) ions and deprotonated cysteine has been carried out by Mori and co-workers.[10] While the lack of water molecule (n=0) resulted in the loss of CO_2 during the optimization step, the most stable forms optimized when the complexes are microsolvated by one or two molecules of water, systematically implied deprotonation of the thiol group. For one water ligand, that this for the $[M(H_2O)(Cys\text{-}H)]^+$ complex, a similar tridentate $[O,N,S^-]$ coordination scheme involving the carbonyl oxygen, the nitrogen and deprotonated sulfur was found for Zn^{2+}, Cd^{2+} and Hg^{2+}. The amount of charge transfer to the metal is much more pronounced for Hg than for Cd or Zn, (+0.90e, +1.37e, +1.41e, respectively). Adding a second water ligand or using a polarized continuum model resulted in a preferred bidentate conformation for Cd and Hg (N,S^-), whereas Zn remains tricoordinated. Mori and co-workers also estimated the binding energy of the bare dications with neutral cysteine and found the following order Zn(II)> Hg(II)>Cd(II), in agreement with a previous study.[7] The estimated values turned to be significantly larger with the B3LYP functional as compared to CCSD(T) calculations. This trend was later confirmed by Ahlstrand et al.[30], who compared the binding energy computed by four different functionals (B3LYP, B98, TPSSh, M06) to CCSD(T) estimates, for complexes of Zn^{2+} or Cd^{2+} with amino acid mimics (acetate, methanethiolate, and imidazole) or water.

Whereas DFT functionals overestimate the magnitude of the interaction energy, on the other hand they correctly predict the structure of the complexes generated in the

gas phase by the interaction of Zn^{2+} or Cd^{2+} with a single amino acid (aa), as evidenced by numerous combined theoretical/IRMPD (InfraRed Multiple Photon Dissociation) studies. IRMPD spectroscopy of mass-selected ion is now established as a powerful approach for the structural characterization of gaseous metal ions/biomolecules complexes.[31-34] P. B. Armentrout and co-workers have carried out an extensive study about the interactions taking place in the gas phase between Zn^{2+}, Cd^{2+} and a series of aminoacids.[15-25, 35-37] Regardless the type of complexes generated by electrospray, namely $[Cd(aa)-H]^+$ or $[CdCl(aa)]^+$, these studies show that a systematic agreement is observed between the DFT-computed ground state and the experimental IRMPD spectra, and that Cd interacts through a tridentate binding scheme with a charge-solvated form of the amino acid, involving the backbone nitrogen, the oxygen of the carbonyl of the carboxylic group and a heteroatom of the side chain. In several studies, the same complexes could be observed for both Zn and Cd. This is the case of the $[Zn(aa)-H]^+$ and $[Cd(aa)-H]^+$ ions (aa=Cys, His),[15, 16] or $(MCl(Met)]^+$,[25] and the two metals are found to share the same binding scheme, with shorter interacting distances for Zn due to smaller ionic radius and stronger electrostatic interactions. This is illustrated for instance by the $[Zn(cys)-H]^+$ and $[Cd(cys)-H]^+$ ions, which could be generated from acetonitrile adducts produced by electrospray and irradiated by a continuous wave CO_2 laser. These two complexes exhibit similar IRMPD action spectra which are in very good agreement with tridentate conformers involving thiol group deprotonation, like those found previously.[10] The same tridentate interaction is also observed for $[Cd(His)-H]^+$ and $[CdCl(His)]^+$, except the carboxylic acid is deprotonated and there is no spectator Cl^- ion in the former. Structural assignment turned to be more complicated when the metal is surrounded by two amino acids. In a recent study[24], the structure of the computed ground state of $[Cd(His)(His-H)]^+$ indeed differed according to the theoretical methods used, due to very small relative energies between structures involving either a zwitterionic or a canonical intact histidine. IRMPD data tend to suggest a mixture of the two forms.

Metal ions play different roles in nucleic acids systems depending on the type of the metals.[38, 39] While alkali metals often bind to phosphate groups to DNA and RNA strands, transition-metal ions predominantly interact directly with nucleobases, and the following affinity order holds for the nucleic acid monomers: N7(guanosine) > N3-(cytidine) > N7(adenosine) > N1(adenosine) > N3(adenosine, guanosine).[40, 41] We have also mentioned the particular affinity of Hg^{2+} to the T-T pair (*vide infra*). Cadmium has been classified as a category 1 human carcinogen and cadmium-induced carcinogenicity

can involve direct interaction of cadmium with DNA.[42] This has motivated different fundamental studies about the interaction of Cd with different DNA building blocks, and notably nucleobases. In a computational study, Burda and co-workers aimed at characterizing the binding characteristics of a series of divalent metal ions (including Cd^{2+}) towards canonical forms of adenine (A) and guanine (G), [43] by considering planar *Cs* structures of the M^{2+}/nucleobase complexes, with metal cations interacting with the nitrogen N7 of adenine and N7 and O6 of guanine.



R=H : uracile
R=CH_3 : thymine

cytosine

adenine

guanine

All the intermolecular M-N7 distances for adenine-containing complexes were found shorter than the corresponding distances in guanine, due to the fact that the interaction is monodentate for the former and bidentate for the latter. The binding energy of G turned to be systematically larger than that of A, regardless the metallic center, with values estimated at -197 and -124 kcal/mol for Cd^{2+} at the MP2 level (including BSSE corrections). Later, Wu and co-workers reinvestigated the interactions of Cd^{2+} with adenine by considering different tautomeric forms.[44] Their DFT study (B3LYP) showed that the prevailing structure was not the canonical form but involved an imino tautomer with interaction of the metal with both N7 and N6 nitrogen atoms. Similarly, the most stable structure of the Cd^{2+}/thymine (T) complex also involved a keto-enol tautomeric form of T. To account for the influence of solution environment, they also performed PCM calculations, which resulted in a significant decrease in the relative energies between the different structures and a change of the global minimum. The interaction with the five nucleobases were also investigated by Bachi and co-workers.[45] Their B3LYP results are in agreement with those of Wu and co-workers concerning the Cd^{2+}/nucleobase complexes: a bidentate interaction with a tautomeric form of U, T and A, and with a canonical form of G and C. Using the global minimum for each nucleobase resulted in the following order of metal ion affinity for Cd: A>G>T>U>C. This order slightly changes when considering only canonical forms (C>G>A>T>U). Effects of Cd

complexation onto the Watson-Crick base pair stability has also been investigated, by considering interaction of the dication with only the purine bases (with nitrogen N7 of adenine in the AT pair and with nitrogen N7 and oxygen O6 of guanine in the GC pair).[43] The presence of the metal induces a significant perturbation of the Hydrogen bond network between the base pairs, Cd^{2+} and Hg^{2+} having a similar effect. The pyrimidine base turned to have a negligible effect onto the metal/purine complex, but it was observed that the stabilization energy resulting from the metal/purine base interaction was reduced when the nucleobase was engaged in the base pair. The interaction with the purine is significantly reduced when the metal is hydrated.[46] Complexes in which cadmium directly interacts with two nucleobases have also been studied, both theoretically[44] and experimentally.[47, 48] Fridgen and co-workers studied different $[M(uracil\text{-}H)(uracil)]^+$ complexes (M=Zn, Cu, Ni, Co, Fe, Mn, Cd, Pd, Mg, Ca, Sr, Ba, or Pb) by combining SORI-CID (Sustained-Off Resonance Irradiation) and IRMPD to DFT calculations.[47] These complexes could be divided into two families depending on whether they dissociate according to loss of intact uracil or HNCO (which involved C2 and N3 atoms). Regardless the metal ion, the most stable computed structure involves a metal ion ligated by N3 and O4 of deprotonated uracil and by N3 and O2 of intact uracil in its O4H tautomeric form. The differences in the observed fragmentations for the $[M(Ura{-}H)(Ura)]^+$ complexes when M=Zn, Cu, Ni, Fe, Cd, Pd, Ca, and Mg on one hand and when M=Sr, Ba, and Pb on the other hand can be explained, in part by the computed binding energies between uracil and $[M(Ura\text{-}H)]^+$, loss of intact uracil being observed for metals having the lowest binding energies (Sr, Ba and Pb). It was also found that the computed binding energies between uracil and the$[M(Ura\text{-}H)]^+$ ions globally increased as the ionic radius decreased. This group also performed IRMPD experiments on the ammoniated complexes $[[M(Ura{-}H)(Ura)NH_3]^+$.[48] The spectra of the Fe, Co, Ni, Zn, and Cd complexes are all strikingly similar and are consistent with an ammonia molecule coordinated to the metal.

To complete this bibliographic compilation, deliberately focused on the interactions of cadmium with compounds of biological interests, other gas-phase studies published recently could also be mentioned. Some provided new insights about the effect of cadmium exposure onto the plant metabolome[49, 50] or antibiotics.[51] Given the high toxicity of cadmium, many efforts are also devoted to the design of new chelates for sensitive and selective detection of Cd at low concentration and in this context, different fundamental studies about the interactions of Cd^{2+} with different mono or multidentate

organic ligands were reported.[52-60] Finally, one may also mention a very nice series of studies unveiling unexpected reactions of Group IIb metal ions.[61-64]

Hg

Probably one of the first studies of the biochemical role of Hg was done by Katz in 1952, who observed that mercury chloride was able to react with salts of nucleic acids leading to a decrease in the viscosity.[65] In following years more papers were published on the peculiarities of the interaction between Hg^{2+} and DNA,[66] finding that the reaction could be reversed by adding complexing agents for Hg^{II}. A decade after the first paper aforementioned, Katz went a step further in the binding mechanism of Hg^{II} ions with polynucleotides, concluding that in the interaction with the T-T base pair Hg^{II} was coordinated to both N3 positions of the two thymine residues.[67] Later on the crystal and molecular structure of a 2:1 complex of 1-methylthymine-Hg^{II} would be reported,[68] showing that the structure was stabilized indeed by a N-Hg-N bond linking the two thymine moieties together.

We needed to wait to the first years of the 21st century to witness a significant activation of the research on the interactions between Hg^{II} and DNA, strongly motivated by the high toxicity of this metal and by the necessity of finding strategies able to detect mercury ions in the environment. As a first significant result, in 2004 it was found that the binding of Hg^{II} ions to thymine-thymine (T–T) base pairs was not only strong but also highly selective in clear contrast with other transition metal ions, such as Cu^{2+}, Ni^{2+}, Pd^{2+}, Co^{2+}, Mn^{2+}, Zn^{2+}, Pb^{2+}, Cd^{2+}, Mg^{2+}, Ca^{2+}, Fe^{2+} and Ru^{2+} that do not affect in a significant manner duplex stability.[69] Thus, the possibility of generating selective sensors for Hg^{2+} was really high through its interaction with T-T pairs. Little later, new experimental results would confirm that the stabilizing effect of Hg^{2+} on the T-T base pair surpasses the effects of other metals and seems to be highly specific.[70] A posterior analysis of ^{15}N-^{15}N J-coupling across Hg^{II} provided a direct evidence for the formation of T-Hg^{II}-T pairs. These conclusions were coherent with the results obtained through the use of electrospray ionization mass spectrometry (ESI-MS), fluorescence and circular dichroism (CD) spectroscopy.[71] It was also found that the T–Hg^{II}–T base pair plays a role in the biochemistry of polymerases opening new possibilities for the metal-ion-mediated enzymatic incorporation of a variety of artificial bases into oligonucleotides.[72] Rather interestingly it was also reported that the thermal stability of the duplex DNA with the T-Hg-T base pair is comparable to that of the corresponding T:A or A:T base pairs.[73] In the

same paper the binding constant for the specific binding of Hg^{2+} to a T:T mismatch was reported.[73] Also, new ESI-MS/MS studies on selected oligodeoxynucleotides rich and poor in thymine indicated that Hg^{II} prefers thymines over the other binding sites in oligonucleotides both in solution and in the gas phase.[74] An interesting computational study[75] along with the experimental data reported by Miyake et al.[70] mentioned above, provided a very interesting information on the structural properties, electronic structure and UV absorption spectra of the (T–Hg^{II}–T) base pair, showing not only the nature of the Hg-N bonding but also that the metal–metal interaction between two Hg^{II} in multiple stacking T–Hg^{II}–T is the origin of the significant changes in the UV absorption spectra. Similar results were obtained by means of electrospray ionization-tandem mass spectrometry.[76] The role of metal-base pairs in DNA-like materials with a superior conductivity and their use for new nano-electronic applications was analyzed in this period too.[77]

Ono et al.[78] reported the synthesis of covalently linked parallel and antiparallel DNA duplexes containing the metal-mediated base pairs T–Hg^{II}–T, and an interesting review on the binding of metal ions by pyrimidine base pairs in DNA duplexes.[79] Later on, new perspectives on the incorporation of Hg^{2+} into DNA Duplex,[80] on the role of Hg^{2+} in the stability of duplexes with non-canonical dU–dU pairs,[81] on the expansion of the concept to metal-mediated base triples and base tetrads,[82] and on its effects on the thermal stabilities of DNA duplexes containing homo- and heterochiral mismatched base pairs,[83] would be also reported.

Specific studies in this field were devoted to DNA damage[84-86] induced by Hg^{II}, to the role of Hg^{2+} on the construction of DNA molecular logic gates that produce electrochemiluminescent signals,[87] and to the photoluminescent properties of phenylmercury(II) complexes.[88]

In relation to the formation of the T-Hg^{II}-T base pairs, is particularly important the role played by the so-called nucleophilic attraction.[89] This phenomenon , as pointed out by Benda et al.,[90] is behind the stabilizing effect that $Hg^{II}\cdots Hg^{II}$ non-covalent interactions between the consecutive Hg^{II}-mediated base pairs have on the nucleic acid structures. Subsequent studies by Raman spectroscopy[91] and theoretical calculations[92] would confirm these first conclusions. More recently, Hg^{II} was also found to bind C-T mismatches with high affinity,[93] and that the formation of these Hg^{II}-mediated base pairs can be triggered by irradiation with light.[94] The three-dimensional structure of metallo-DNA with consecutive T–Hg^{II}–T base pairs also confirm the critical role of the

$Hg^{II}\cdots Hg^{II}$ non-covalent interactions in the stabilization of the 3D building, explaining at the same time the positive entropy for the metallo-base pair formation.[95] Along these lines, the first crystal structure reported for a DNA duplex containing two consecutive T–Hg^{II}–T base pairs showed structural features, such as N3-Hg and Hg^{II}-Hg^{II} distances fully compatible with the previous studies on these systems, suggesting that the metallophilic attraction could certainly stabilize the B-form of the double helix.[96] Results obtained from DFT calculations on $(T\text{-}Hg\text{-}T)_3$ and $(U\text{-}Hg\text{-}U)_3$ were consistent[97] with these experimental observations. Little later, the first determination of the one-bond $^1J(^{199}Hg,^{15}N)$ coupling characterizing the unique physicochemical properties of the N–Hg^{II} interactions in T-Hg^{II}-T systems, was reported.[98] Although, to the best of our knowledge, the first fluorescence study on T–Hg^{II}–T base pairs was reported in 2008,[99] the most complete characterization of the fluorescence of this system would be reported eight years later through the use of the thymidine analogue ^{DMA}T that exhibits the same base pairing preferences as native thymine residues.[100] In this way, it was possible to show that the fluorescence properties of ^{DMA}T-A base pairs reflected the exceptionally high kinetic stability of T-Hg^{II}-T base pairs and that they could have a high potential to disrupt DNA metabolism in vivo.[100] Later on, highly sensitive fluorometric methods for the determination of Hg^{II} ions were described.[101] A study of the interactions of Hg^{II} with T-T mispair containing hairpin loops, including UV-visible thermal circular dichroism analyses,[102] demonstrated that the number of T-T mispairs in oligonucleotide probes plays an important role for Hg (II) binding, presumably due to an increase in cooperative binding.

One very interesting application of metal-mediated base pairs is their use as metal-ion sensors.[103] This is particularly the case when dealing with T-Hg^{2+}-T base pairs,[104] due to the high toxicity of Hg^{2+} cations. Also, the fact that Hg^{2+} is capable of forming T-Hg-T base pairs and that Hg^{2+} can be reduced to $(Hg_2)^{2+}$ was the base to generate fluorescence sensors.[105] Similarly, the stabilization of T:T mismatches by Hg^{2+} ions, may be used for the detection of single nucleotide polymorphisms.[104] Also, voltammetric[106] new electrochemical DNA-based biosensors based on blue modified electrodes[107] and on ligase mediated creation of G-quadruplex-hemin DNAzyme[108] were designed for the selective determination of the Hg_2. Interesting are the applications in generating DNA nanomachines.[109] Other potential uses have been described in some interesting feature articles.[110, 111]

Although most of the publications compiled in the previous paragraphs were focused on the interaction of different forms of mercury with thymine, some attention was also paid to the interactions with other biochemical bases. As suitable examples the theoretical study of the interactions of cysteine with Cu^{2+}, Zn^{2+}, Cd^{2+} and Hg^{2+} using DFT calculations, [7] the experimental and theoretical investigation of the photophysics and photochemistry of Hg^{2+} with mono- and bisporphyrins,[112] the binding of Hg^{2+} with cysteine, dipeptide Cys-Gly and reduced glutathione by electrospray ionization mass-spectrometry and isothermal titration calorimetry,[113] the design of new methods for removal of Hg(II), based on the appealing interaction between Hg^{2+}, exfoliated graphene oxide (EGO) and L-cystine,[114] or the investigation of the properties of 5-mercurycytosine, [115] should be mentioned.

In any overview on the biochemistry of mercury, it is necessary to remember that this element can be present not only as Hg^{2+} but in other chemical forms. Among them, methylmercury (CH_3Hg^+) has received also much attention, because, due to its high liposolubility which allows it to easily pass through the cell membranes, becomes one of the most toxic forms of mercury.[116] On the other hand, though it is a much softer acid than the proton, CH_3Hg^+ reacts strongly with aminoacids[117] and shows an extremely high affinity for cystine and polypeptide residues.[118] The sequestering ability of some S, N, and O donor ligands towards CH_3Hg^+ was evaluated showing that all S donor ligands show a good sequestering power.[119] In our group we have also investigated the gas-phase interactions of uracil and thymine with alkylmercury cations, in particular CH_3Hg^+, n-$BuHg^+$ and t-$BuHg^+$ in a combined experimental and theoretical approach.[120] A combination of electrospray ionization coupled to tandem mass spectrometry Infrared Multiple Photon Dissociation (IRMPD) techniques and DFT calculations allowed us to conclude that the aforementioned ions exhibit a peculiar reactivity characterized by the transfer of the alkyl group to the nucleobases, the dominant reaction being the alkylation of the nucleobase, $[R(NB)]^+$ with the concomitant loss of neutral Hg.[120]

We have cited in previous paragraphs papers in which different experimental techniques were nicely complemented by different computational approaches to address structural and bonding questions related with complexes involving Hg. Here, we will pay attention to studies done exclusively on theoretical grounds with the aim of improving the knowledge on the structural and bonding characteristics of the complexes between Hg^{2+} and CH_3Hg^+ and different biochemical systems. Although no biochemical systems are involved, our first citation should correspond to the Filatov and Cremer's pioneering

work on the bonding of mercury chalcogenides,[121] because it contributes significantly to understand the bonding characteristics of an element for which this information is extremely scarce. Indeed, very few theoretical studies on the bonding between biochemical systems and Hg can be reported. Among them, the Hg binding to biothiols[122] or to flurbiprofen,[123] the complexes of Hg^{II} with sulfur- and aminopyridine-containing chelating resins,[124] and the interaction of Hg^{2+} cations with the most stable tautomeric forms of free DNA and RNA bases,[45] should be reported. To finish this compilation, the paper on spodium bonds, which refer to a net attractive interaction between any element of Group 12 (Zn,Cd, Hg) and electron-rich atoms should be cited because it provides a bonding analysis that can be useful to understand the structure and stability of biochemical systems interacting with these three metals.[125]

Pb

Lead is a normal constituent of the earth's crust (approx. 20 ppm), with trace amounts found naturally in soil, plants, and water. Lead, probably before the Bronze or Iron Ages, was used in some cultures in medicine and cosmetics (*kohl*) because of abundance and ease in obtaining it. Due to anthropogenic activities, lead is commonly found in our groundwater and accumulated in waste, but its use is likely to be rare in modern age because the lead toxicity is well known, as long-term exposure or inhalation of lead can cause death. Since its dangerousness is very high many studies are already underway to eliminate it using different inorganic molecules,[126] of which superchalchogens are a good recent example.[127] Not surprisingly there is a particular interest on its effects in biological homeostasis,[128] and consequently many studies in the literature have focused their attention on the specific toxic effects on human health.[129-131] These harmful effects usually affect major organs including liver, heart and kidneys.[128, 132] Lead can be in an ionic form or as an oxide, but both are toxic though the former is more reactive and interacts more easily with organic molecules. Indeed the number of chemical reactions in which it can participate, probably due to a high affinity for proteins forming bioaccumulative harmful adducts in the human body is very large.[133] The first evidence was reported as early as 1952, by Klotz et al.[134] on the absorption spectra on [Pb(II)] binding to proteins adducts.

To review recent studies on molecules interacting with lead, it is reasonable to remember that this metal tends to easily associate with electron donors such as oxygen, nitrogen and sulfur.[135, 136] In molecules similar to porphyrin, lead as a dication is usually

bound to nitrogen atoms through a dative bond. Recent synthesis, characterization and computational studies of tetraacetamide derivatives of tetraazacycloalkane as ligand with this metal show this type of bonding.[137] The *peri*-substituted naphthalene and bis(5-(pyrazin-2-yl)-1,2,4-triazol-3-yl) methane interaction with Pb(II) also evidence such an association.[138, 139] If one replaces nitrogen with an oxygen atom, one can find crown ether derivatives that also have electronic pairs available in their central atoms. Nevertheless, the crown cavity is smaller than the metal size which leads to metal sandwich complexes formation, and the interaction can be found with both the monocation and the dication. A study performed by Franski using collision-induced dissociation tandem mass spectrometry showed how singly charged sandwich complexes between ether crown and lead can be easily formed after removing a hydrogen atom.[60] At the same time, doubly charged sandwich complexes have also been detected but they were difficult to generate experimentally.[60] In addition to interactions in which the cavity is formed only by nitrogen or oxygen, cases in which the cavity involves both atoms have also been studied. This is the case of the interaction of ethylenediaminetetraacetic acid (EDTA) anions (i.e. $[EDTA\text{-}nH]^{n-}$, n=1–4) with Pb(II) where the metal could coordinate with two nitrogens and two or even 4 oxygen atoms.[140] This process is followed, as revealed by mass spectrometry,[140] by removal from the ligand up to a maximum of 4 protons, leaving a complex where lead is hexacoordinated,[140] though other fragmentation observed involves the loss of CO_2. Due to the easy deprotonation of aminoacids when interacting with Pb^{2+}, most of the studies deal with the resulting monocations. The most recent publication on this topic deals with the interaction between L-proline and Pb^{2+} where $[Pb(Pro\text{-}H)]^+$ complexes are characterized at the X3LYP and M06-L levels of theory.[141] Likely, the most extensive study dealing with amino acids was reported by Fridgen et al.[142] and dates back to a decade ago. In this study eight $[Pb\text{-}(amino\ acid\text{-}H)H_2O)]^+$ complexes have been explored by blackbody infrared radiative dissociation (BIRD) and computational formalisms. The amino acids explored were Gly, Ala, Val, Leu, Ile, Phe, Glu, and Lys which have shown that there is a link between their gas-phase basicities and the ability of resulting deprotonated species $[Pb(amino\ acid\text{-}H)]^+$ to attach water, since amino acids with stronger basicities donate more electron density to Pb^{2+} and weaken its bond with the water oxygen. The values of the binding energies with water induced by the presence of lead estimated at the B3LYP level range from 77 to 114 kJ/mol^{-1}. Consistently, the same year Bohme et al.[143] published a study of 15 deprotonated amino acids after interacting with lead(II). In this case the lead dication and complexes were electro-

sprayed from solution and subjected to collision-induced dissociation in a tandem mass spectrometer. The C-αC bond of the amino acid was found to be activated by Pb^{2+} by the same mechanism that influences the gas-phase acidities of the amino acids. Bond activation by Pb^{2+} appears to be the largest with deprotonated glycine[144, 145] and is also large with the other deprotonated amino acids containing hydrocarbon side chains (alanine, proline and valine). Later on, an IRMPD spectroscopy study together with computational analyses were carried out to determine the structures of deprotonated Phenylalanine and Glutamic acid with Pb(II).[146] It was shown, both on experimental and theoretical grounds, that the proton is removed from the carboxylic group whereas the metal bidentates between the amino group and the carbonyl of the amino acid, and that the interaction of water in $[Pb(Phe\text{-}H)H_2O)]^+$ and $[Pb(Glu\text{-}H)H_2O]^+$ gives rise to a tetracoordinated lead structure in the gas phase.

Although our objective is to discuss the interactions of lead with different molecules of biological interest, and not to discuss and analyze the different types of lead coordination, this analysis can be found in the review published by Aboutorabi et al.[147]

Concerning the interaction of nucleobases with lead, the first reported study was focused on uracil and thymine.[148, 149] The presence of two different carbonyl types and the deprotonation induced by Pb^{2+} were explored by means of mass spectrometry and theoretical calculations. The metal interacts preferentially with the oxygen at position 4 after removing the hydrogen ligated to the nitrogen at position 3. Also, the cleavage of the most important fragments (PbNCO and HNCO) was elucidated. Similar conclusions were reported for thiouracil derivative,[150] though in this case the metal preferred interaction site is always the sulfur atom. For 2,4-dithiouracil the interaction takes place at position 4, and the deprotonation takes place from the same nitrogen atom as in uracil and thymine. In $[Pb(cytosine\text{-}H)]^+$ many patterns of lead interaction are repeated.[151] The bonding is bidentate with the carbonyl oxygen atom and the adjacent nitrogen, as confirmed by IRMPD spectra. The deprotonation involves in this case the NH group at position 1. In all the cited molecules, lead activates the cleavage of C1-N3 bond to eliminate HNCO. If we switch to the deprotonated dimer of uracil with lead, $[Pb(Ura\text{-}H)Ura]^+$, the interaction is tetradentate involving the same active sites as above.[152] The deprotonation is at the same site and the metal binds to two nitrogen and two oxygen atoms, because an internal hydrogen transfer is observed involving the NH group of the other monomer. The loss of HNCO in this case is not observed but the departure of an

uracil molecule occurs instead.[153] It is worth noting that this study was done recovering the interaction of deprotonation of uracil dimer with other heavy metals such as Zn, Cu, Ni, Co, Fe, Mn, Cd, Pd , Mg, Ca, Sr, and Ba (see also Cd section, *vide supra*).

As far as we know the reactivity of the complexes between adenine and guanine and lead was not explored. On the other hand, complexes generated in the gas phase between Pb^{2+} and deprotonated 2'-deoxyguanosine-5'-monophosphate (dGMP), 2'-deoxycytidine-5'-monophosphate (dCMP), cytidine-5'-monophosphate (CMP) and uridine-5'-monophosphate (UMP) were studied both computationally and by IRMPD spectroscopy.[154-156] All these complexes are found to be macrochelates, involving simultaneous interaction of the metal with the deprotonated phosphate group and the nucleobase moiety. Remarkably, in the particular case of UMP, the binding scheme involves a tautomeric form of uracil.[155]

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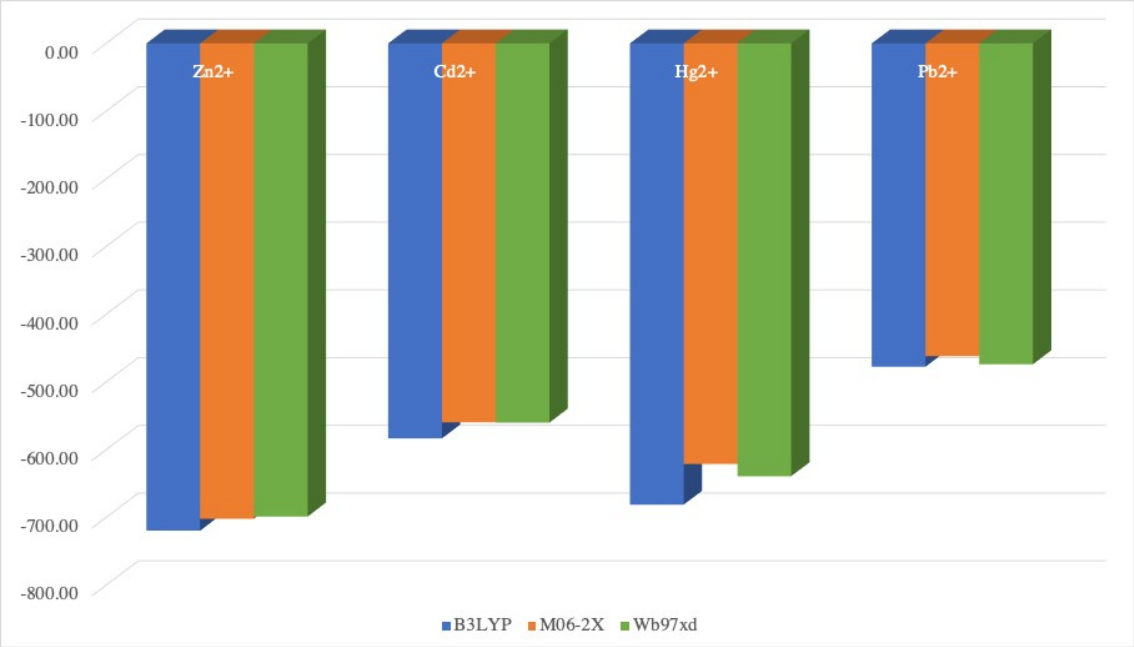

Figure S1. Comparison of the calculated binding energies (kJ·mol^{-1}) for urea-M^{2+} (M = Zn, Cd, Hg, Pb) complexes obtained with three different density functional theory methods, namely, B3LYP, M06-2X and ω-B97XD.

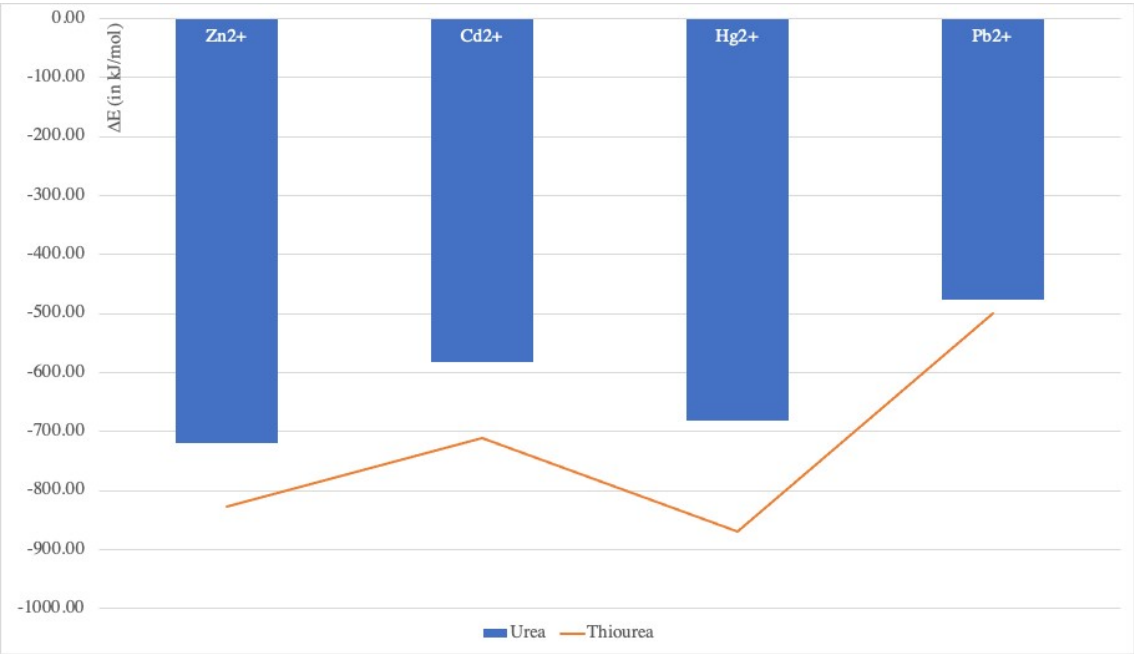

Figure S2. Variation of the calculated binding energies (kJ·mol^{-1}) for urea-M^{2+} (blue histogram) and thiourea-M^{2+} (orange line) (M = Zn, Cd, Hg, Pb) complexes.

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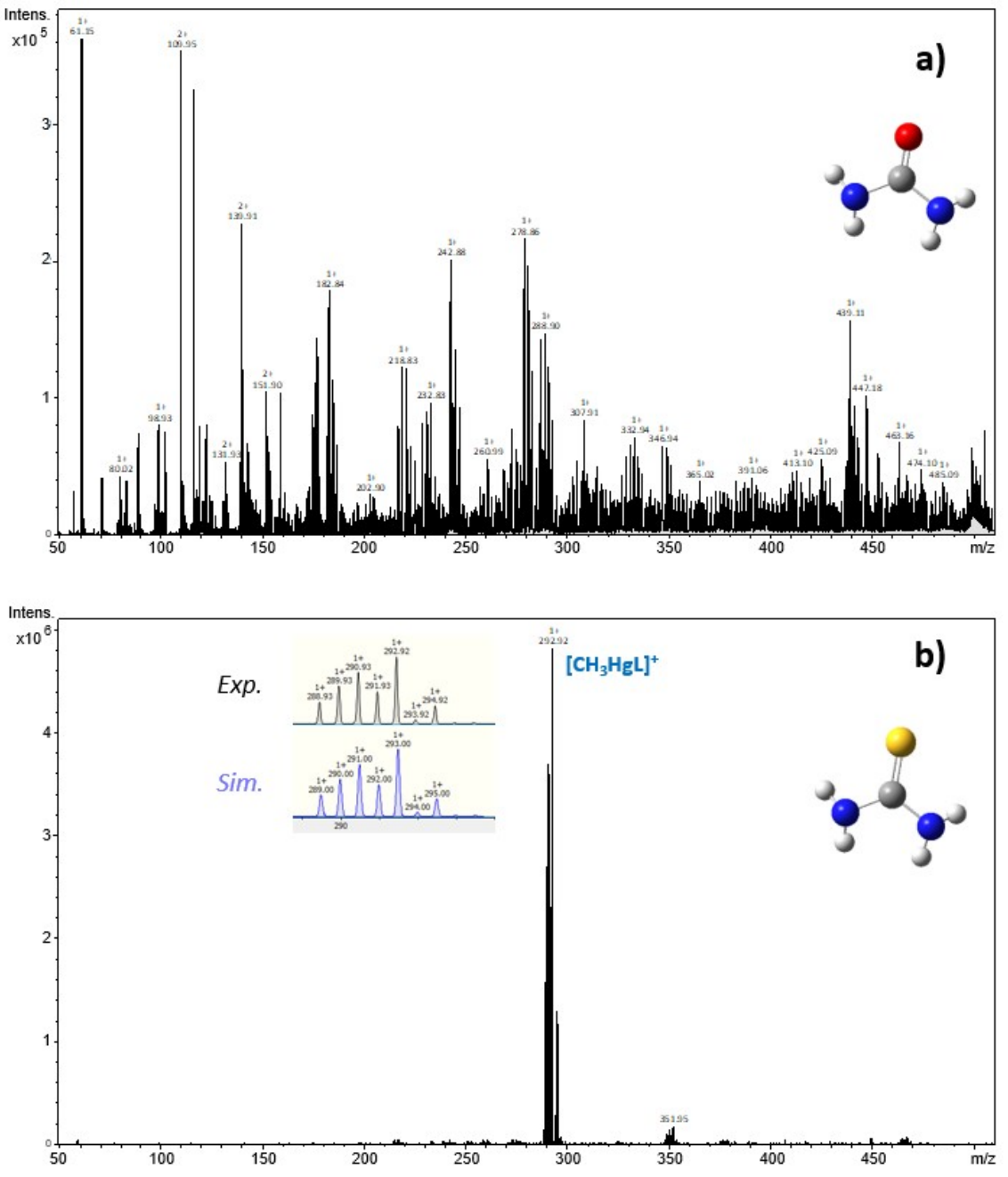

Figure S3. Positive-ion electrospray spectrum of an equimolar solution of CH_3HgCl and ligand L (10^{-4}M) in a water/methanol mixture (50/50 v/v) with **a)** L=urea and **b)** L=thiourea.
Mass spectra recorded on a Bruker Amazon speed ETD ion trap (capillary voltage: -4500V; dry gas: 4 L/min; nebulizer gas: 7.25 psi; dry temp: 180 °C; Cap Exit: 140 V ; Trap Drive 43.5; End plate offset: -500V; flow rate: 3 µl/min)

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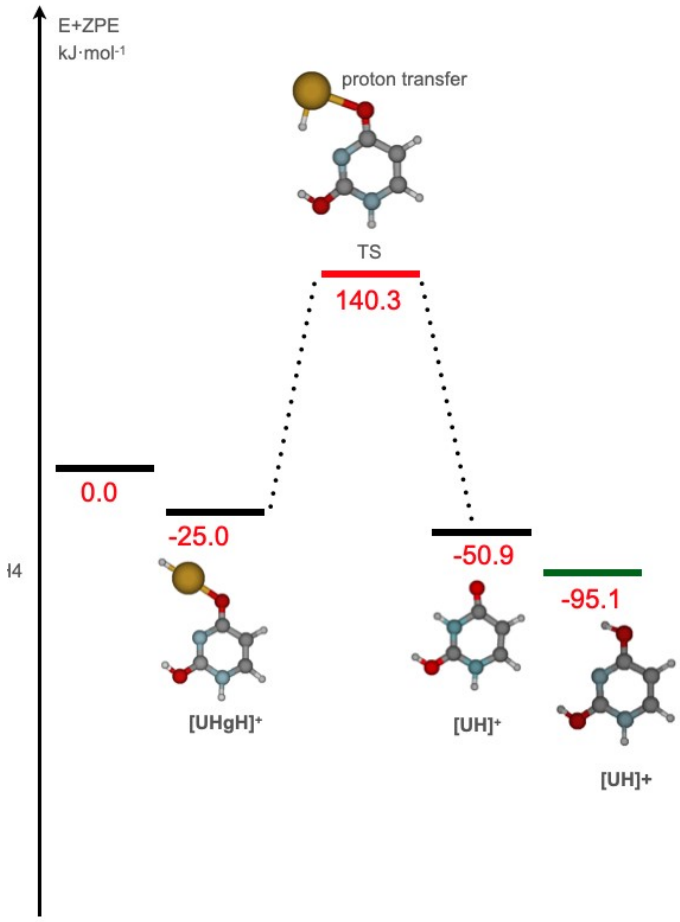

Figure S4. Proton transfer reaction from [UHgH$^+$] resulting from the beta-hydride elimination (Figure 3) to give protonated uracil. Relative energies plus zero-point energy (kJ·mol^{-1}) are shown in red color.

Table S1. Isomers of ethyl uracil cations [UEt]$^+$ at the B3LYP/6-31++G(d,p) level of theory. Energies are shown in kJ·mol^{-1}.

Keto forms	**E + ZPE**	**H**	**H rel**
U1	-493.62048	-493.61020	165.7
U2c	-493.65544	-493.64503	74.3
U2d	-493.65320	-493.64274	80.3
U3	-493.62583	-493.61542	152.0
U4a	-493.66781	-493.65756	41.4

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U4b	-493.66508	-493.65484	48.6
U5	-493.64098	-493.63061	112.2
U6	Converged to U5		112.2
Enol forms			
E_U1a	-493.66996	-493.65990	35.2
E_U1b	-493.66523	-493.65508	47.9
E_U1c	-493.65192	-493.64160	83.3
E_U1d	-493.65035	-493.64001	87.5
E_U3a	-493.67016	-493.66009	34.8
E_U3b	-493.66628	-493.65616	45.1
E_U3c	-493.65657	-493.64623	71.1
E_U3d	-493.65343	-493.64297	79.7
E_U6a	-493.68236	-493.67210	3.2
E_U6b	-493.67798	-493.66763	15.0
E_U6c	-493.66555	-493.65507	47.9
E_U6d	-493.66323	-493.65268	54.2
E_U4ac	-493.66041	-493.65025	60.6
E_U4bc	-493.66685	-493.65668	43.7
E_U4ad	-493.64589	-493.63548	99.4
E_U4bd	-493.65426	-493.64388	77.3
E_U2ac	-493.66103	-493.65080	59.1
E_U2bc	-493.66773	-493.65756	41.4
E_U2ad	-493.64822	-493.63797	92.8
E_U2bd	-493.65689	-493.64671	69.9
Dienol forms			
dE_U1ac	-493.66410	-493.65416	50.3
dE_U1ad	-493.64880	-493.63865	91.0
dE_U1bc	-493.67059	-493.66069	33.2
dE_U1bd	-493.65721	-493.64714	68.8
dE_U3ac	-493.64445	-493.63421	102.7
dE_U3ad	-493.66009	-493.65008	61.0
dE_U3bc	-493.63512	-493.62457	128.0

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dE_U3bd	-493.65333	-493.64318	79.1
dE_U6ac	-493.67651	-493.66637	18.3
dE_U6ad	-493.66169	-493.65130	57.8
dE_U6bc	-493.68343	-493.67333	**0.0**
dE_U6bd	-493.67039	-493.66007	34.8
dE'_U6ac	-493.65814	-493.64768	67.3
dE'_U6ad	-493.67228	-493.66209	29.5
dE'_U6bc	-493.65006	-493.63926	89.4
dE'_U6bd	-493.66584	-493.65548	46.9

Table S2. Isomers of ethylmercury uracil cations $[EtHg(U)]^+$ at the B3LYP/6-31++G(d,p)/DEF2-TZVPP level of theory. Energies are shown in $kJ \cdot mol^{-1}$.

Keto forms	**E + ZPE**	**H**	**H rel**
U1	-647.18844	-647.17502	116.3
U2c	-647.22409	-647.21080	22.3
U2d	-647.22179	-647.20840	28.6
U3	-647.19544	-647.18200	97.9
U4a	-647.23241	-647.21930	0.0
U4b	-647.22998	-647.21773	4.1
U5	-647.20184	-647.18850	80.9
U6	Converged to U5		80.9
Enol forms			
E_U1a	-647.22220	-647.20911	26.7
E_U1b	-647.21730	-647.20410	39.9
E_U1c	-647.20703	-647.19461	64.8
E_U1d	-647.20232	-647.18982	77.4
E_U3a	-647.22661	-647.21350	15.2
E_U3b	-647.22257	-647.20941	26.0
E_U3c	-647.21400	-647.20066	48.9
E_U3d	-647.21040	-647.19783	56.4
E_U6a	-647.19929	-647.18718	84.3

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E_U6b	-647.19467	-647.18245	96.7
E_U6c	-647.18204	-647.16872	132.8
E_U6d	-647.17986	-647.16742	136.2
E_U4ac	-647.21854	-647.20549	36.3
E_U4bc	-647.22705	-647.21409	13.7
E_U4ad	-647.20378	-647.19042	75.8
E_U4bd	-647.21558	-647.20236	44.5
E_U2ac	-647.22585	-647.21288	16.9
E_U2bc	-647.23153	-647.21862	1.8
E_U2ad	Conv. to E_U2ac		16.9
E_U2bd	Not converged		-
Dienol forms			
dE_U1ac	-647.21670	-647.20370	41.0
dE_U1ad	-647.19777	-647.18629	86.7
dE_U1bc	-647.22322	-647.21027	23.7
dE_U1bd	-647.20629	-647.19396	66.5
dE_U3ac	-647.19995	-647.18753	83.4
dE_U3ad	-647.21755	-647.20542	36.4
dE_U3bc	-647.18631	-647.17426	118.3
dE_U3bd	-647.20879	-647.19649	59.9
dE_U6ac	-647.19330	-647.18128	99.8
dE_U6ad	-647.17857	-647.16630	139.2
dE_U6bc	-647.20003	-647.18805	82.1
dE_U6bd	-647.18708	-647.17395	119.1
dE'_U6ac	-647.16874	-647.15638	165.2
dE'_U6ad	-647.18305	-647.17095	126.9
dE'_U6bc	Not converged		-
dE'_U6bd	-647.17642	-647.16414	144.8