Theoretical Isotope Fractionation of Cadmium during Complexation with Organic Ligands

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Abstract: Cadmium (Cd) isotopes are an important tool to better understand both inorganic and organic geochemistry of Cd, and organic ligands play a key role to control the toxicity and mobility of Cd in living organisms and also in terrestrial and aquatic environments. Knowledge of the equilibrium isotope fractionation of Cd with organic ligands is crucial to further advance Cd isotope source and [process tracing in the field of biogeochemistry](#). In this study, we calculated reduced partition function ratios ($10^3 \ln \beta$) of Cd isotopes in various organic Cd complexes by density functional theory. The calculation results show that the $10^3 \ln \beta$ of $^{114}\text{Cd}/^{110}\text{Cd}$ for these complexes are decreased in the order of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^- > \text{Cd}(\text{cit})(\text{H}_2\text{O})_3^- > \text{CdH}(\text{cit})(\text{H}_2\text{O})_4 > \text{CdEDTA} > \text{Cd}(\text{his})_2\text{H}_2\text{O} > \text{Cd}(\text{cit})_2^{4-} \approx \text{Cd}(\text{H}_2\text{O})_6^{2+} > \text{Cd}(\text{H}_2\text{O})_4^{2+} > \text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+} > \text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-} > \text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^- > \text{Cd}(\text{DMPS})_2^{4-}$ at 0 ~ 100°C, and heavy Cd isotopes preferably bind to oxygen and nitrogen donor atoms while light Cd isotopes bind to sulfur donor atoms of organic ligands. Thus, the previously observed immobilization of light Cd isotopes in living organisms could be related to Cd detoxification processes with sulfur. The predicted equilibrium isotope fractionation will strengthen Cd isotopes as a process tracing tool in these systems and will improve the understanding of Cd isotope cycling in aquatic and terrestrial systems.

Keywords: Cd isotope; Organic complexes; Equilibrium isotope fractionation; O/N/S donor; Density functional theory; Isotope biogeochemistry

1. Introduction

Cadmium (Cd) is a non-essential element for most living organisms (Sigel et al., 2013). It is ubiquitous in terrestrial and aquatic environments where it can occur naturally or through anthropogenic activities (Kabata-Pendias, 2011; Liu et al., 2017). Being very mobile, it is readily taken up by living organisms (Khan et al., 2014; Thévenod et al., 2019), where it can impair the organisms itself (Sigel et al., 2013) and/or it can be further transported along the food chain and accumulated in animals and humans (Fransson et al., 2014; Satarug et al., 2010). Thus, the understanding of processes that control the fate of Cd in the terrestrial and aquatic environments are crucial.

Isotope geochemistry has been increasingly applied in the past years for tracing anthropogenic Cd pollution (Cloquet et al., 2006; Salmanzadeh et al., 2017; Imseng et al., 2018; Yang et al., 2019), tracing the source of ore-forming fluids (Zhu et al., 2016), to advance the understanding of the past and present marine biogeochemical cycling of Cd (Lambelet et al., 2013; Zhang et al., 2018; Sieber et al., 2019), as well as to trace processes that control the Cd homeostasis in unicell organisms (Horner et al., 2013; Moore et al., 2020) and distinct types of plants such as grasses (Wiggenhauser et al., 2016; Imseng et al., 2018; Wiggenhauser et al., 2021; Zhang et al., 2021), cacao (Barraza et al., 2019; Moore et al., 2020), and Cd accumulating plants (Wei et al., 2016; Zhou et al., 2020). Cd has eight stable isotopes which atomic masses range from 106-116, their ratios can vary significantly in the environment

(Hoefs, 2015). Cd isotope fractionation in terrestrial and aquatic systems is generated by multiple processes such as sorption to reactive surfaces (Wasylenki et al., 2014), precipitation of Cd into minerals (e.g., calcite, Horner et al., 2011; Guinoiseau et al., 2018; sphalerite, Zhu et al., 2013), membrane transport (Wei et al., 2016), weathering (Zhang et al., 2016; Zhu et al., 2018), binding to inorganic materials (Wasylenki et al., 2014; Yang et al., 2015; Guinoiseau et al., 2018), and complexation with organic ligands as shown for other metals (Morgan et al., 2010; Ryan et al., 2014; Marković et al., 2017). Once isotope fractionation factors are defined for these processes, Cd isotopes can provide novel information about major biogeochemical processes that control the mobility of Cd in complex terrestrial and aquatic systems. For Cd, binding to organic ligands plays a crucial role in detoxifying, sequestering and separating toxic Cd from essential nutrients in living organisms (Wang and Wang, 2009; Cao et al., 2018; Le Croizier et al., 2019). Recent studies showed that Cd isotopes are strongly fractionated in living organisms which has been attributed to processes such as membrane transport (Moore et al., 2020) and Cd binding to organic ligands (Wiggenhauser et al., 2016, 2018, 2021). For the latter, it was hypothesized that Cd binding to reduced sulfur groups (R-SH, thiols) in the bacteria *E.coli* to detoxify Cd resulted in an enrichment of light isotope in membranes (Horner et al., 2013). Furthermore, cereals strongly retained light Cd isotopes in roots which lead to an enrichment of heavy isotopes in shoots and grains (Wiggenhauser et al., 2016; Imseng et al., 2019; Wiggenhauser et al., 2021; Zhang et al., 2021). The immobilization of light isotopes was ascribed to binding of Cd to thiols to detoxify and sequester Cd in

roots and shoot parts and to avoid accumulation of Cd in grains (Wiggenhauser et al., 2016). Together, studies in living organisms proposed that sulfur (S) involved detoxification and immobilization processes of Cd could be a major driver of Cd isotope fractionation. However, no isotope fractionation factor for Cd binding to distinct organic ligands exist yet, which makes it difficult to interpret Cd isotope fractionation in complex biological systems.

During the past few years, calculating isotope fractionation for distinct metal complexes has significantly improved metal isotope process tracing applications in complex biogeochemical systems (Fujii and Albarède, 2012; Moynier et al., 2013; Fujii et al., 2014; Wiederhold, 2015; Albarede et al., 2016; Moynier and Fujii, 2017). For inorganic Cd complexes, theoretical calculations predicted that Cd hydroxides and Cd nitrates are isotopically heavier compared to hydrated Cd while hydrated Cd is heavier than Cd chlorides and hydrosulfide (Yang et al., 2015). Guinoiseau et al. (2018) recently verified these in a Cd sulfide precipitation experiment which revealed that Cd light isotope was enriched in sulfide and that the enrichment of light isotope decreased with increasing chloride concentration in solution. For organic ligands, either experimental or theoretical Cd isotope fractionation data of Cd organic complexes has not been studied. Such Cd isotope fractionation data would be particularly useful to improve Cd isotope process in tracing complex biogeochemical systems where organic ligands play a crucial role on the fate of Cd in the environment. Here, we aimed to strengthen Cd isotope process tracing approaches by applying density functional theory (DFT) to calculate Cd hydrated complexes

$\text{Cd}(\text{H}_2\text{O})_4^{2+}$ and $\text{Cd}(\text{H}_2\text{O})_6^{2+}$; Cd-citrate complexes $\text{Cd}(\text{cit})_2^{4-}$, $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$,
 $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$; CdEDTA; Cd-histidine $\text{Cd}(\text{his})_2\text{H}_2\text{O}$; Cd-DMPS
complexes $\text{Cd}(\text{DMPS})_2^{4-}$ and $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$; Cd-cysteine $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$; Cd-
glutathione complex $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$. The obtained results were discussed regarding
its implications for past and future Cd isotope processes tracing approaches.

2. Theory and methods

2.1. Cd organic complexes

Oxygen (O), nitrogen (N), and sulfur (S) are abundant elements that essential for all
living organisms. In organic ligands, they serve as donor atoms to bind metals such as
Cd as part of organic complexes such as citrate (cit) (McLean et al., 2013; Panfili et
al., 2009; Zorrig et al., 2010), histidine (his) (Wierzbicka et al., 2007; Gunawardana et
al., 2010; Hoch et al., 2012; Colaneri et al., 2013), Ethylenediaminetetraacetic acid
(EDTA) (Kovács et al., 2010), cysteine (cys) (Leitenmaier et al., 2011; Cao et al.,
2014; Smith et al., 2015), glutathione (GSH) (Prévéral et al., 2009; Seth et al., 2011;
Wu et al., 2013), and dimercaptopropane sulfonic acid (DMPS) (Zeini Jahromi et al.,
2014). These complexes are involved in controlling uptake, transport, and
sequestration of Cd in living organisms, whereas EDTA and DMPS are model
compounds for strong chelating complexes. EDTA represents chelators with O and N
donors such as nicotianamine (Clemens et al., 2013; Marković et al., 2017;

Puschenreiter et al., 2017) and DMPS represents strong chelators with S donors such as phytochelatin (Marentes and Rauser, 2007; Pal et al., 2019).

2.2. Calculations

Equilibrium isotope exchange reaction between two metal complexes can be represented by:

where Y denotes one element that is represented by light (Y) and heavy isotopes (Y^*). A and B represent two different ligands. Ligands and isotopes of Y form the chemical complexes AY and BY . The isotope fractionation factor α between the complexes AY and BY is defined as:

$$\alpha_{AY-BY} = K_{eq} = \frac{\beta_{AY}}{\beta_{BY}} \quad (2)$$

the isotope fractionation factor is expressed in permill [‰]:

$$10^3 \ln \alpha_{AY-BY} = 10^3 \ln \beta_{AY} - 10^3 \ln \beta_{BY} \quad (3)$$

In these equations, K is the equilibrium constant, which is equal to the α of the isotope exchange reaction of chemical complexes (AY , BY) that exchange the same element (Y). β is the reduced partition function ratio (RPFR). Bigeleisen and Mayer (1947) and Urey (1947) suggested that equilibrium mass-dependent isotope fractionation factors results from the molecular vibrational frequencies. β can be calculated as:

$$\beta_{114-110} = \prod_i \frac{{}^{114}U_i e^{-{}^{114}U_i/2}}{{}^{110}U_i e^{-{}^{110}U_i/2}} \frac{1 - e^{-{}^{110}U_i}}{1 - e^{-{}^{114}U_i}} \quad (4)$$

U_i and v_i are defined as:

$$U_i = hv_i/kT \quad (5)$$

Here, h , k , and T refer to the Planck's constant, Boltzmann constant and absolute temperature, respectively. v_i is the harmonic vibrational frequency of the i th vibrational mode in s^{-1} . The number of vibrational modes for non-linear molecules is $3n-6$ (n is the number of atoms in the molecule), $3n-5$ for linear molecules.

In this study $^{114}\text{Cd}/^{110}\text{Cd}$ isotope ratios were chosen to study the Cd isotope fractionation of Cd partitioning into different chemical complexes. The $^{114}\text{Cd}/^{110}\text{Cd}$ is a widely used isotope ratio in experimental (Rehkämper et al., 2011; Horner et al., 2013; Pallavicini et al., 2014; Chrastný et al., 2015; Wei et al., 2016; Li et al., 2018) and theoretical studies (Yang et al., 2015). Gaussian 09 (Dennington et al., 2009; Frisch et al., 2009) was used to calculate the geometries optimization and vibrational frequencies of Cd species using Becke-style 3-parameter (B3) density functional theory with the Lee-Yang-Parr (LYP) correlation functional (Lee et al., 1988; Becke, 1993a, b). In this study, the mixed basis sets were used, for H, C, N, O, and S, the all-electron basis set 6-311+G(d, p) was used (Clark et al., 1983; Francel et al., 1982; Krishnan et al., 1980; McLean and Chandler, 1980; Spitznagel et al., 1987); for Cd, an effective-core potential (ECP) basis set LanL2DZ was chosen (Hay and Wadt, 1985). The “ultrafine” numerical integration grid was used and the molecular geometries were optimized without any forced symmetry for all complexes. The setting of exchange correlation functionals may have effect on the calculated vibrational frequencies, and four exchange correlation functionals B3LYP, BVP86,

B3PW91 and PBEPBE were tested. For $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$, the mean square errors of the calculated vibrational frequencies of the four exchange correlation functionals are 366.90, 874.94, 1084.19 and 7440.05 respectively (Table S1), the calculated frequencies by B3LYP are more consistent with the experimental results and the B3LYP functional was chosen to estimate the isotope fractionation of Cd complexes in this study.

3. Results and discussion

3.1. Optimized molecular geometries

The optimized geometries of the organic Cd complexes are shown in Fig. 1. For comparison, Table 1 lists the optimized bond lengths calculated by this study, and previously published theoretical and experimental data. Donor atoms, optimized coordinated bond lengths (Å) and mean bond lengths (Å) are shown in Table S3 (Supplementary material). The optimized Cd-O distances of $\text{Cd}(\text{H}_2\text{O})_4^{2+}$ and $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ (Fig. 1a, b) by using the basis set 6-311+G(d, p) are consistent with those by using the basis set 6-31+G(d, p) (Yang et al., 2015).

For Cd-citrate complexes: $\text{Cd}(\text{cit})_2^{4-}$, $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$, $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$, the deprotonated carboxyl groups in Cit^{3-} are always coordinated to the central Cd^{2+} (Bertoli et al., 2015). The d10 electron configuration of Cd^{2+} favors sixfold coordination and forms octahedral geometry (Siddiqui et al., 2011), while in

less bulky ligands, Cd^{2+} tends to form tetrahedral coordination complexes (Ramalho and Figueroa-Villar, 2002; Bertoli et al., 2015). $\text{Cd}(\text{cit})_2^{4-}$ (Fig. 1c) and $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ (Fig. 1d) with fourfold coordination complexes, are adducts of two citrate molecules and have several isomers in solution (Bertoli et al., 2015). They differ in their protonation and each of the two citrate molecules provided two carboxylate oxygen atoms to coordinate to Cd^{2+} . The coordinated bond lengths of $\text{Cd}(\text{cit})_2^{4-}$ and $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ were 2.21, 2.22 Å and 2.14-2.38 Å respectively. The Cd atoms in $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ (Fig. 1e) and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$ (Fig. 1f) were sixfold coordinated, their bond lengths were 2.24-2.40 Å and 2.24-2.43 Å, respectively.

CdEDTA (Fig. 1g) is sixfold coordinated, and EDTA provides two N and four O donor atoms for Cd^{2+} . The stronger binding of Cd^{2+} to N than to O, and the electrostatic attraction induced by the carboxylate result in a high stability for CdEDTA (Kovács et al., 2010; Karak et al., 2016). The calculated Cd-O and Cd-N distances (Cd-O: 2.26, 2.36; Cd-N: 2.48, Table 1b) in this study were close to those calculated by Kovács et al. (2010). Cd-histidine ($\text{Cd}(\text{his})_2\text{H}_2\text{O}$, Fig. 1h) is also sixfold coordinated and contains an imidazole ring, carboxyl and amino groups that provide four N and two O donor atoms for Cd^{2+} (Colaneri et al., 2013). The calculated distances were 2.26 Å for Cd-O 2.41-2.48 Å for Cd-N (Table 1b).

The ligand DMPS contains two thiolate groups and one sulfonate group, and the thiol groups of the DMPS chelate Cd^{2+} in fourfold coordination (Zeini Jahromi et al., 2014, Fig. 1i and 1j). For 1:1 Cd-DMPS complexes, the calculated average distance of Cd to its S donor atoms was 2.48 Å. For 1:2 Cd-DMPS complexes, the average bond

distance to four S donor atoms was 2.69 Å. The calculated bond lengths were consistent with the previously published values (Table 1b) (Zeini Jahromi et al., 2014).

For $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$ (Fig. 1k), the thiol group of cysteine tends to bind the metal ion by S donor atoms when cysteine is present in excess (Jalilehvand et al., 2009; Fujii et al., 2014). In our study, Cd was bound to three water molecules and one thiol group of cysteine, the bond length of Cd to its S donor atoms was 2.48 Å, which was slightly shorter than the experimental data of Cd-cysteine 2.52-2.54 Å (Jalilehvand et al., 2009). Glutathione, γ -Glu-Cys-Gly, is a thiol-containing tripeptide, and the ligands of 1:2 Cd-glutathione complexes (Fig. 1l) are GS^{3-} molecules with amide protons, where Cd has a tetrahedral coordination sphere and the complex primarily involves two deprotonated thiol groups from cysteine residues and two water molecules (Delalande et al., 2010). EXAFS spectra of Cd-glutathione complexes suggested Cd was fourfold coordination and S atoms were identified as the binding atoms at 2.54 ± 0.1 Å (Isaure et al., 2015). The calculated Cd-S mean bond distance in this study was in agreement with previous EXAFS result (2.545 Å) (Table 1b).

3.2. Comparison with experimental vibrational frequencies

Only a few experimentally determined vibrational frequencies exist for organic Cd complexes since they are difficult to determine experimentally. Richet et al. (1977) thought the effects of anharmonicity on the isotope fractionation are expected to be

quite small, here only harmonic vibration was considered. Table 2 lists the calculated harmonic vibrational frequencies of the ^{114}w isotopomer and ^{110}w isotopomer of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ and the experimental data by FTIR (Bertoli et al., 2015). The frequency shifts values $10^3(1 - ^{114}\text{w}/^{110}\text{w})$ of Cd isotopes are also listed.

In Table 2, w_1 is the twisting vibration mode of H-C-H with stretching vibration mode of C-O, the experimental vibrational frequencies by Bertoli et al. (2015) was 1027.05 cm^{-1} , the calculated data by this study were 1041.1681 cm^{-1} for ^{114}w isotopomer and 1041.1686 cm^{-1} for ^{110}w isotopomer, the average value of the calculated frequency of the two isotopomers is about 1.375% higher than experimental data. w_2 is the rocking vibration mode of H-C-H with stretching vibration mode of C-C, the experimental data was 1078.98 cm^{-1} , the calculated frequencies were 1079.978 cm^{-1} for Cd heavy isotope and 1079.9783 cm^{-1} for the light one, the average frequency values by this calculation is 0.093% higher than experimental data. w_3 is the twisting vibration mode of H-C-H with stretching vibration mode of C-C, the calculated average data is 1.041% lower than experimental data. w_4 is the scissoring vibration mode of H-C-H, the average data by calculation is close to the experimental data and the calculated average frequency is 0.490% lower than experimental data. w_5 is the rocking vibration mode of H-C-H with stretching vibration mode of C-C and C-O, the average data by calculation is 0.698% higher than experimental data. w_6 is the wagging vibration mode of H-C-H with scissoring vibration mode of O-H, the frequency difference between experiment and the average theory calculation is 0.142%. The w_7 is the symmetrical stretching vibration and the

difference between calculation and experiment is 0.310%. w_8 is the symmetrical stretching vibration mode of COO^- , the difference of calculated data and experimental data is 0.069%. w_9 is asymmetrical stretching vibration of COO^- , the average frequency calculated is 3.187% higher than experimental results. For w_{10} , it is stretching vibration mode and the calculated result is 0.652% lower than experimental data (Table 2). Overall, the calculated frequencies were generally consistent with previously experimental data of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$.

The accuracy of vibrational frequencies can be further propagated in the final $10^3\ln\beta$ values (Schauble et al., 2003, 2004; Schauble et al., 2007). Frequency scaling factors can often be used to correct the calculated vibrational frequencies which are able to reproduce the experimental frequencies. However, the simple harmonic frequency calculated by quantum chemistry methods need to be corrected when it is used to calculate isotope fractionation involving larger molecules (Liu et al., 2010; Fujii et al., 2014). Here frequency scaling factors were not needed in this study.

3.3. Reduced partition function ratios, $10^3\ln(\beta_{114-110})$ for Cd complexes

In nature, mass-independent Cd isotope effects may not be significant and mass dependent effects are the main factor for naturally occurring Cd isotope variations (Rehkämper et al., 2011). [Here](#), only the mass-dependent isotope effects for various Cd species have been studied. The calculated reduced partition function ratios $10^3\ln(\beta_{114-110})$ of the Cd complexes with varying temperatures from 0 °C to 100 °C

calculated in this study are reported in Table 3. ^{114}Cd and ^{110}Cd have the largest mass difference among Cd isotopes (Carignan et al., 2004; Wombacher and Rehkämper, 2004), usually $^{114}\text{Cd}/^{110}\text{Cd}$ isotope ratios were chosen to study the Cd isotope fractionation of Cd partitioning into different chemical complexes. Mass-dependent isotope fractionation is a function of temperature (T), and can be expressed as below:

$$10^3 \ln(\beta_{114-110}) = A \times \frac{10^6}{T^2} + B \quad (6)$$

Where A , B are the regression parameters, which can be figured out from Table 3. The A , B values of these complexes are listed in Table S2, for comparison their relationship also be figured in Fig. 2. Our calculation shows that the $10^3 \ln \beta$ of $^{114}\text{Cd}/^{110}\text{Cd}$ for these complexes decreases in the order of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^- > \text{Cd}(\text{cit})(\text{H}_2\text{O})_3^- > \text{CdH}(\text{cit})(\text{H}_2\text{O})_4 > \text{CdEDTA} > \text{Cd}(\text{his})_2\text{H}_2\text{O} > \text{Cd}(\text{cit})_2^{4-} \approx \text{Cd}(\text{H}_2\text{O})_6^{2+} > \text{Cd}(\text{H}_2\text{O})_4^{2+} > \text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+} > \text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-} > \text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^- > \text{Cd}(\text{DMPS})_2^{4-}$ at $0 \sim 100^\circ\text{C}$.

Previous studies demonstrated that the types of donor atoms (O, N, S) of organic ligands are a main driver for Zn isotope fractionation (Albarède et al., 2011; Fujii and Albarède, 2012; Balter et al., 2013; Moynier et al., 2013; Fujii et al., 2014). Particularly, O donors preferentially bind heavier Zn isotopes than S donors. Cd and Zn are in the same group in the periodic table which means that the two elements have the same number of electrons in their outer valence shell. Thus, the elements share similar chemical properties such as a flexible coordination chemistry, they are non-redox sensitive, and have similar stability constants (John et al., 2017; Maret and Moulis, 2013; Sóvágó and Várnagy, 2013). It is likely that O, N, and S donor atoms

may have a similar effect on Cd isotope fractionation as they do for Zn. This hypothesis has been recently partly verified by Yang et al. (2015) who reported an enrichment of heavy Cd isotopes for O and N compared to S donors of inorganic ligands. In addition, studies on Zn isotopes have shown that the number of coordination for the same donor atoms can also determine isotope fractionation (Fujii et al., 2014). For instance, fourfold coordinated Zn-amino acid complexes had larger $10^3\ln(\beta_{114-110})$ values than the sixfold coordinated complexes of the same amino acid. The relationship between the $10^3\ln(\beta_{114-110})$ values and donor atoms type of the Cd complexes at 25°C is given in Fig. 3 (the types and numbers of donor atoms are given in Table S3). For Cd complexes, S or combinations of S and O donor atoms tended to complex with lighter Cd isotopes. Furthermore, the $10^3\ln(\beta_{114-110})$ disparities induced by S and S/O donor atoms were bigger than those by O and O/N donor atoms. The relationship between $10^3\ln(\beta_{114-110})$ and mean bond lengths of Cd to its donor atoms at 25°C was shown in Fig. 4. Overall, mean coordinated bond lengths of complexes with O donor atoms were shorter than those with S donor atoms, except $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$. The reason may be that $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$ has three O donors and one S donor.

Among all studied Cd complexes, $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ has the largest $10^3\ln(\beta_{114-110})$ values while $\text{Cd}(\text{DMPS})_2^{4-}$ has the smallest $10^3\ln(\beta_{114-110})$ values (Fig. 2 and Table 3), their difference can reach 1.18 at 25°C. Cd-citrate complexes can be fourfold coordinated ($\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ and $\text{Cd}(\text{cit})_2^{4-}$) and sixfold coordinated ($\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$), and their $10^3\ln(\beta_{114-110})$ values can differ up to 0.213 at 25°C which means that the structure difference of these Cd-citrate complexes can result in

Cd isotope fractionation (Fig. 1, 2). In addition, $10^3\ln(\beta_{114-110})$ values of fourfold coordinated $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ were larger than those of sixfold coordinated $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$, but those of $\text{Cd}(\text{cit})_2^{4-}$ are smaller than those of $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$. Thus, for Cd-citrate complexes, the coordination number is only one of the factors that have an effect on Cd isotope fractionation, when estimating Cd isotope fractionation of them, other factors should be considered.

The Cd-cysteine, Cd-GSH, and Cd-DMPS complexes contain S donor atoms. Our calculations revealed that these Cd complexes had lower $10^3\ln(\beta_{114-110})$ values in comparison with hydrated Cd complexes and organic Cd complexes that contained O and N donor atoms (Table 3 and Fig. 3). The lower $10^3\ln(\beta_{114-110})$ values in S containing ligands is in agreement with previous studies that reported $10^3\ln\beta$ values for inorganic Cd (Yang et al., 2015) and organic Zn complexes (Fujii et al., 2014). Among the complexes that contained S and O donor atoms in this study, their $10^3\ln(\beta_{114-110})$ values slightly differed. For instance, $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$ and $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$ were complexed with two S donor atoms from the organic molecules and two O donor atoms from water molecules. The average bond lengths of Cd-S in $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$ (2.48 Å) was shorter than that in $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$ (2.545 Å, Table 1 and S3). The average Cd-O bond lengths in $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$ (2.95 Å) were longer than that of $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$ (2.415 Å). Our data suggests that chelators with S ligands significantly change the bond lengths between Cd and other donor atoms than S which might contribute to the lower $10^3\ln(\beta_{114-110})$ value in the chelating $\text{Cd}(\text{DMPS})_2^{4-}$ complex.

As anticipated, the $10^3\ln(\beta_{114-110})$ values of $\text{Cd}(\text{DMPS})_2^{4-}$, a Cd chelating complex with four S and no O donor atoms, was smaller compared to $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$ (Table 3 and Fig. 3). This observation agrees with previously published calculations of Zn sulfides where the smallest fractionation occurred in Zn sulfide complexes with four S donor atoms compared to Zn sulfide complexes contained mixtures of S and O donor atoms (Fujii et al., 2011). Together, our data suggests that a large shift towards light isotopes occurs when Cd is complexed to a chelating organic ligand with two or four S donor atoms when compared non-chelating S donor atoms and O/N donor atoms in general.

Experimentally obtained isotope fractionation factors for Zn (Marković et al., 2017) and Cu (Ryan et al., 2014) complexes reported a direct relation between the stability of complexes and the extent and isotope fractionation factors. This relation was also observed in our data, however, the difference of $10^3\ln(\beta_{114-110})$ values between metal chelator CdEDTA and $\text{Cd}(\text{his})_2\text{H}_2\text{O}$ was comparably small (0.027 at 25°C, Fig. 2 and Table 3). Though CdEDTA forms more stable complexes than Cd-histidine complexes (Sóvágó and Várnagy, 2013; Karak et al., 2016), the coordination number was six for both complexes while the CdEDTA had four O and two N donor atoms and $\text{Cd}(\text{his})_2\text{H}_2\text{O}$ had four N and two O donor atoms, and the average bond lengths between the central Cd atom and its donor atoms were very similar: CdEDTA 2.367 Å (Cd-O: 2.26, 2.36 Å; Cd-N: 2.48 Å); $\text{Cd}(\text{his})_2\text{H}_2\text{O}$ 2.378 Å (Cd-O: 2.26 Å; Cd-N: 2.41-2.48 Å, Table S3 and Fig. 4). Hence, the small differences in Cd isotope fractionation between the two complexes might have been demonstrated by the

distinct coordination and bond lengths of the two complexes.

3.4. Error analysis for Cd isotope fractionation

Vacuo and solvation models can cause isotope fractionation factors inaccuracies (Hill and Schauble, 2008; Yang et al., 2015). In ideal vacuum gaseous conditions, the influence of the surrounding environment such as solvents on the solute molecules in the real system is ignored. To overcome this limitation, some solvent models were established to simulate the effects of solvents on solutes. The polarized continuum models (PCMs) are widely used to simulate the aqueous environment (Tomasi et al., 2005; Tsepis, 2014). However, Yang et al. (2015) found that the bond lengths optimized by IEFPCM model are larger than those by vacuo model and the $10^3\ln(\beta_{114-110})$ results calculated in the IEFPCM model are smaller than those in vacuo model, and thought that the optimized structures and $\ln\beta$ values of Cd complexes calculated in vacuo are more consistent with the experimental data. For comparison, the implicit solvation models IEFPCM (the integral-equation-formalism versions of PCM) and CPCM (conductor-like PCM) were used to calculate the optimized molecular structures and $10^3\ln(\beta_{114-110})$ at 25°C for studied complexes (Table S4 and S5), as well as the model of $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ with second hydration sphere $\text{Cd}(\text{H}_2\text{O})_{18}^{2+}$ (Table S6). Our calculation showed that most of the bond lengths optimized in solution by this study were larger than those in vacuum (Table S4). This was agreement with the results of inorganic Cd complexes (Yang et al., 2015). For $10^3\ln(\beta_{114-110})$ values, not

only does difference exist between two implicit models and vacuum model but also between two implicit models. By comparing with vacuum model, IEFPCM and CPCM solvation models decrease the $10^3 \ln \beta$ of $\text{Cd}(\text{H}_2\text{O})_4^{2+}$ by 0.346 and 0.221 at 25°C respectively, and increase the $10^3 \ln \beta$ of $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ by 0.139 and 0.166 at 25°C respectively. For $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$, $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$, $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$ and $\text{Cd}(\text{his})_2\text{H}_2\text{O}$, IEFPCM and CPCM model decrease the $10^3 \ln \beta$ by 0.175-0.580 and 0.206-0.567 and increase the $10^3 \ln \beta$ of $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$ by 0.281 and 0.401 at 25°C respectively. For $\text{Cd}(\text{cit})_2^{4-}$, CdEDTA , $\text{Cd}(\text{DMPS})_2^{4-}$, these two models increase the $10^3 \ln \beta$ by less than 0.1 at 25°C. For $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$, the IEFPCM solvation model decrease the $10^3 \ln \beta$ by 0.109 and CPCM model increase the $10^3 \ln \beta$ by less than 0.1 at 25°C, the implicit solvation models have different effects on Cd isotope fractionation (Table S5). The main reason may be that the simple harmonic vibrational frequencies have been polluted by translation and rotation which make the inaccurate for frequencies data in solvation models (Yang et al., 2015), and the levels of “pollution” may be different for different Cd complexes.

Setting the second hydration sphere is able to make the calculated frequencies closer to the experimental values and improve the $10^3 \ln \beta$ for Ni and Zn (Fujii et al., 2014), the same phenomenon may occur in Cd hydrate species. Our calculation showed that for $\text{Cd}(\text{H}_2\text{O})_6^{2+}$, the $10^3 \ln \beta$ values for the explicit model as $\text{Cd}(\text{H}_2\text{O})_{18}^{2+}$ is 2.377 and 1.990, 1.923 for explicit model + IEFPCM and explicit model + CPCM at 25°C respectively. Compared with the vacuum model, the explicit model increases the $10^3 \ln \beta$ values and explicit + implicit model decrease them (Table S6). The total

symmetric stretching mode of hexaaqua complexes, ν_1 CdO_6 , is shown in Table S6. The calculated ν_1 frequency values of large cluster $\text{Cd}(\text{H}_2\text{O})_{18}^{2+}$, $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ + IEFPCM and $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ + CPCM are closer to previous calculation and experimental data than that of $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ (Table S6), which means solvation models make the frequency values closer the literature values and the solvent effect on $10^3\ln\beta$ values are needed to be considered.

Frequency is another most frequently mentioned factor that may cause uncertainties or errors of the calculated reduced partition function ratios (Schauble et al., 2003, 2004; Schauble et al., 2007; Méheut et al., 2007, 2009; Weeks et al., 2007; Yang et al., 2015). For lack of experimental vibrational frequency of Cd organic complexes, it is impossible to evaluate the RPFR errors for them, and different vibration frequencies may lead to discrepant uncertainty in $10^3\ln(\beta_{114-110})$ values at 25 $^\circ\text{C}$ (Vogt et al., 1993; Schauble, 2007; Yang et al., 2015). Based on existing experimental frequency data of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ and this calculation, the maximum difference between them is 3.187%, and the average deviation is about 0.293%. Based on Schauble (2007, 2011), calculated frequencies may lead to an error of less than 0.6% for $10^3\ln(\beta_{114-110})$ values of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$.

3.5 Implications for Cd process tracing applications in biogeochemistry, supergene geochemistry and environmental science

Metal isotope fractionation can be used to trace processes that control the

distribution of an element in terrestrial and aquatic environments. Previous experimental studies hypothesized that the Cd isotope fractionation is strongly linked to Cd speciation to organic ligands with S donor atoms to detoxify and immobilize Cd in living organisms (Horner et al., 2013; Wiggenhauser et al., 2016, 2021; Imseng et al., 2019). Results by this study and Yang et al. (2015) revealed that an enrichment of light isotopes occurs in thiol ligands when compared to hydrated Cd and Cd bound to O/N donor atoms of organic ligands, which will strengthen not only Cd isotopes as a process tracing tool, but also the understanding of Cd isotope cycling in aquatic and terrestrial systems. For example, to reduce inputs of the toxic trace metal Cd into the food chain of humans and animals, processes that control the mobility of Cd in terrestrial and aquatic environments need to be well understood. The results that heavy Cd isotopes preferably bind to oxygen and nitrogen donor atoms while light Cd isotopes bind to sulfur donor atoms of organic ligands compared to hydrated Cd²⁺ provides information on processes on the immobilization of Cd isotopes in living organisms which are related to Cd detoxification processes with sulfur.

Furthermore, the strongest Cd isotope fractionation compared to hydrated Cd occurred in chelating S donor ligands, particularly in a chelating S donor ligand in which Cd is exclusively bound to S. Thus, our data confirms the hypothesis that the retention of light isotopes in roots and shoots of grasses (Wiggenhauser et al., 2016, 2021; Imseng et al., 2019) and membranes of *E.Coli* (Horner et al., 2013) could be induced by the immobilization of light Cd isotopes through strong Cd binding to chelators with S donor atoms such as phytochelatins (Clemens et al. 2019). This

chelation would retain light Cd isotopes e.g., in the roots of cereals, while other chemical Cd species such as hydrated Cd that are enriched in heavy isotopes can be transported by membrane proteins towards the shoot. The Cd isotope fractionation induced by chelating thiols may have implications on Cd isotope fractionation in other plants than grasses. Cd hyperaccumulator plants can cope with high Cd concentrations and store, unlike cereals, the majority of the Cd taken up from soils in their shoots (Zhou et al. 2020). To cope with the high Cd shoot concentrations, Cd is mostly bound to O donor atoms of e.g., organic acids and to a lesser extent to S donors (Tian et al. 2011; Isaure et al. 2015). Based on our findings, the Cd isotope fractionation in Cd accumulating plants could potentially provide novel insights into the role of Cd binding to different donor atoms on the translocation of Cd within the shoot. Recent studies focused on Cd isotope fractionation in cacao since cacao beans often exceed the threshold values for Cd potentially leading to elevated Cd concentrations in chocolate (Moore et al. 2020; Barraza et al. 2019). Similar to grasses such as wheat, rice, and barley, cacao seems to retain Cd and its light isotopes in the roots (Moore et al. 2020). Our findings suggest that Cd binding to thiols may play also a crucial role to retain Cd in roots of cacao and thereby limit the Cd transport into cacao beans.

Our results further suggest that Cd ligands, especially thiols, may play a key role in Cd isotope fractionation in living organisms, soils, and waters. In this study, the Cd isotope fractionation between hydrated Cd and Cd chelated by S donor atoms was ~ 1‰. The largest Cd isotope fractionation that has been observed between roots and shoots of plants that strongly retain light Cd isotopes in roots was around 0.60 ‰

(Wiggenhauser et al. 2016, 2021; Imseng et al. 2018; Moore et al. 2020). The difference between our results and the experimentally determined Cd isotopes fractionation between root and shoots may be caused by additional isotope effects that complement isotope effects at equilibrium. The transfer from root to shoot includes membrane transport (Deng et al. 2019). This transport requires fast binding of Cd to a metal binding site of a membrane protein prior to unidirectional membrane transport (Wang et al., 2014; Zhao et al., 2016). Thus, membrane transport might be at least partly kinetically controlled (Köbberich and Vance, 2017). Kinetically controlled processes favor light isotopes through their faster reaction rates (Wiederhold, 2015) while type of metal binding sites of a membrane transporters (e.g., cysteine, histidine) might play an additional role for isotope fractionation during membrane transport. Together, our results suggest that equilibrium Cd isotope fractionation in plants induced by binding of Cd to organic molecules occur in parallel to kinetic isotope effects.

In soils, sediments, and water, organic matter poses an important binding site for Cd and partly controls the mobility of Cd. For instance, soil organic matter derives from decomposed biomass and provides a mixture of O, N, and S donor atoms for Cd in the solid and liquid phase of the soil (Karlsson et al., 2007; Tiberg et al., 2018). Besides processes such as Cd sulfide precipitation and Cd uptake into phytoplankton, soluble organic ligands might significantly control the Cd distribution in water columns and sediments during the oceanic Cd cycle (Guinoiseau et al., 2018). Our data implies that Cd sorption of Cd to organic matter can enrich or deplete the

hydrated Cd pool in heavy and could provide further insights into the role of specific binding sites of organic matter on Cd cycling in the environment.

4. Conclusion

This study provides a first prediction that describes Cd equilibrium isotope fractionation induced by Cd complexation to organic ligands. The $10^3 \ln \beta$ of $^{114}\text{Cd}/^{110}\text{Cd}$ for these investigated complexes decreased in the order of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^- > \text{Cd}(\text{cit})(\text{H}_2\text{O})_3^- > \text{CdH}(\text{cit})(\text{H}_2\text{O})_4 > \text{CdEDTA} > \text{Cd}(\text{his})_2\text{H}_2\text{O} > \text{Cd}(\text{cit})_2^{4-} \approx \text{Cd}(\text{H}_2\text{O})_6^{2+} > \text{Cd}(\text{H}_2\text{O})_4^{2+} > \text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+} > \text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-} > \text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^- > \text{Cd}(\text{DMPS})_2^{4-}$ at $0 \sim 100^\circ\text{C}$. The sequence reveals that Cd complexation to organic ligands with O and N donor atoms are enriched in heavy isotopes while to organic ligands with S donor atoms are enriched with light isotopes. These results provide important information to advance Cd isotopes as a process tracing tool in complex biological systems and further improve the understanding of Cd isotope cycling in aquatic and terrestrial systems.

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Appendices. Supplementary material

Table S1: Comparing the experimental vibrational frequencies with calculated results ($^{110}\omega$) employed by four different exchange correlation functionals for Cd(Hcit)(H₂cit)⁻. Table S2: The fitting factors A, B for $10^3\ln(\beta_{114-110})=A\times 10^6/T^2+B$ (T is K). Table S3: The donor atoms, coordinated bond lengths (Å) and mean bond lengths (Å) for Cd complexes. Table S4a: Optimized bond lengths (Å) of the Cd hydration complexes and citrate complexes calculated with solvation models. Table S4b: Optimized bond lengths (Å) of the organic Cd complexes calculated with solvation models. Table S5: The $10^3\ln(\beta_{114-110})$ of Cd complexes calculated in vacuo and solvation models (IEFPCM, CPCM) at 25°C. Table S6: The vibrational frequencies ($^{110}\omega$) and $10^3\ln\beta$ values of Cd(H₂O)₆²⁺ and Cd(H₂O)₁₈²⁺.

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Figure Captions:

Fig. 1. Optimized molecular structures for various Cd species. a-b: Cd hydrate; c-f: Cd-citrate, the original source of the structure derives from Bertoli et al. (2015) and Fujii et al. (2012); g: CdEDTA (Kovács et al., 2010); h: Cd-histidine (Colaneri et al., 2013); i-j: Cd-DMPS (Zeini Jahromi et al., 2014); k: Cd-cysteine (Jalilehvand et al., 2009 and Fujii et al., 2014); l: Cd-glutathione (Delalande et al., 2010). Abbreviations are cit (citrate), EDTA (ethylenediaminetetraacetic acid), his (histidine), DMPS (dimercaptopropane sulfonic acid), cys (cysteine), and deprotonated glutathione (GSH) is shown as GS. Symbol keys: H (white), C (grey), N (blue), O (red), S (purple), Cd (yellow).

Fig. 2. Temperature dependence of $10^3 \ln(\beta_{114-110})$ for Cd hydrate, citrate, EDTA, histidine, DMPS, cysteine and glutathione complexes. X-axis shows the function of $10^6/T^2$ (lower shaft) and corresponding temperature (upper shaft, 0-100 K), Y-axis shows the $10^3 \ln(\beta_{114-110})$ values.

Fig. 3. Cd ($^{114}\text{Cd}/^{110}\text{Cd}$) isotopic variations with different donor atoms at 25°C. The complexes with O donor atoms are shown as $\square$; N,O donor complexes as Δ ; S,O donor complexes as $\square$; S donor complexes as $\circ$. For O donor complexes, the order of $10^3 \ln(\beta_{114-110})$ values at 25°C from small to large is $\text{Cd}(\text{H}_2\text{O})_4^{2+} < \text{Cd}(\text{H}_2\text{O})_6^{2+} \approx \text{Cd}(\text{cit})_2^{4-} < \text{CdH}(\text{cit})(\text{H}_2\text{O})_4 < \text{Cd}(\text{cit})(\text{H}_2\text{O})_3^- < \text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$; For N,O donor complexes, the order is $\text{Cd}(\text{his})_2\text{H}_2\text{O} < \text{CdEDTA}$; For S,O donor complexes, the order is $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^- < \text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-} < \text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$; The S donor complex is $\text{Cd}(\text{DMPS})_2^{4-}$.

Fig. 4. Reduced partition function ratios, $10^3 \ln(\beta_{114-110})$ vs. mean bond length (Å) at 25°C. Just as Fig. 3, the complexes with O donor atoms are shown as $\square$, including $\text{Cd}(\text{H}_2\text{O})_4^{2+}$, $\text{Cd}(\text{H}_2\text{O})_6^{2+}$,

952 $\text{Cd}(\text{cit})_2^{4-}$, $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$, $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$; N,O donor complexes as Δ ,
 953 including CdEDTA and $\text{Cd}(\text{his})_2\text{H}_2\text{O}$; S,O donor complexes as $\square$, including $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$,
 954 $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$ and $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$; S donor complex as $\circ$, is $\text{Cd}(\text{DMPS})_2^{4-}$.

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Theoretical Isotope Fractionation of Cadmium during Complexation with Organic Ligands

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Abstract: Cadmium (Cd) isotopes are an important tool to better understand both inorganic and organic geochemistry of Cd, and organic ligands play a key role to control the toxicity and mobility of Cd in living organisms and also in terrestrial and aquatic environments. Knowledge of the equilibrium isotope fractionation of Cd with organic ligands is crucial to further advance Cd isotope source and process tracing in the field of biogeochemistry. In this study, we calculated reduced partition function ratios ($10^3 \ln \beta$) of Cd isotopes in various organic Cd complexes by density functional theory. The calculation results show that the $10^3 \ln \beta$ of $^{114}\text{Cd}/^{110}\text{Cd}$ for these complexes are decreased in the order of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^- > \text{Cd}(\text{cit})(\text{H}_2\text{O})_3^- > \text{CdH}(\text{cit})(\text{H}_2\text{O})_4 > \text{CdEDTA} > \text{Cd}(\text{his})_2\text{H}_2\text{O} > \text{Cd}(\text{cit})_2^{4-} \approx \text{Cd}(\text{H}_2\text{O})_6^{2+} > \text{Cd}(\text{H}_2\text{O})_4^{2+} > \text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+} > \text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-} > \text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^- > \text{Cd}(\text{DMPS})_2^{4-}$ at 0 ~ 100°C, and heavy Cd isotopes preferably bind to oxygen and nitrogen donor atoms while light Cd isotopes bind to sulfur donor atoms of organic ligands. Thus, the previously observed immobilization of light Cd isotopes in living organisms could be related to Cd detoxification processes with sulfur. The predicted equilibrium isotope fractionation will strengthen Cd isotopes as a process tracing tool in these systems and will improve the understanding of Cd isotope cycling in aquatic and terrestrial systems.

Keywords: Cd isotope; Organic complexes; Equilibrium isotope fractionation; O/N/S donor; Density functional theory; Isotope biogeochemistry

1. Introduction

Cadmium (Cd) is a non-essential element for most living organisms (Sigel et al., 2013). It is ubiquitous in terrestrial and aquatic environments where it can occur naturally or through anthropogenic activities (Kabata-Pendias, 2011; Liu et al., 2017). Being very mobile, it is readily taken up by living organisms (Khan et al., 2014; Thévenod et al., 2019), where it can impair the organisms itself (Sigel et al., 2013) and/or it can be further transported along the food chain and accumulated in animals and humans (Fransson et al., 2014; Satarug et al., 2010). Thus, the understanding of processes that control the fate of Cd in the terrestrial and aquatic environments are crucial.

Isotope geochemistry has been increasingly applied in the past years for tracing anthropogenic Cd pollution (Cloquet et al., 2006; Salmanzadeh et al., 2017; Imseng et al., 2018; Yang et al., 2019), tracing the source of ore-forming fluids (Zhu et al., 2016), to advance the understanding of the past and present marine biogeochemical cycling of Cd (Lambelet et al., 2013; Zhang et al., 2018; Sieber et al., 2019), as well as to trace processes that control the Cd homeostasis in unicell organisms (Horner et al., 2013; Moore et al., 2020) and distinct types of plants such as grasses (Wiggenhauser et al., 2016; Imseng et al., 2018; Wiggenhauser et al., 2021; Zhang et al., 2021), cacao (Barraza et al., 2019; Moore et al., 2020), and Cd accumulating plants (Wei et al., 2016; Zhou et al., 2020). Cd has eight stable isotopes which atomic masses range from 106-116, their ratios can vary significantly in the environment

(Hoefs, 2015). Cd isotope fractionation in terrestrial and aquatic systems is generated by multiple processes such as sorption to reactive surfaces (Wasylenki et al., 2014), precipitation of Cd into minerals (e.g., calcite, Horner et al., 2011; Guinoiseau et al., 2018; sphalerite, Zhu et al., 2013), membrane transport (Wei et al., 2016), weathering (Zhang et al., 2016; Zhu et al., 2018), binding to inorganic materials (Wasylenki et al., 2014; Yang et al., 2015; Guinoiseau et al., 2018), and complexation with organic ligands as shown for other metals (Morgan et al., 2010; Ryan et al., 2014; Marković et al., 2017). Once isotope fractionation factors are defined for these processes, Cd isotopes can provide novel information about major biogeochemical processes that control the mobility of Cd in complex terrestrial and aquatic systems. For Cd, binding to organic ligands plays a crucial role in detoxifying, sequestering and separating toxic Cd from essential nutrients in living organisms (Wang and Wang, 2009; Cao et al., 2018; Le Croizier et al., 2019). Recent studies showed that Cd isotopes are strongly fractionated in living organisms which has been attributed to processes such as membrane transport (Moore et al., 2020) and Cd binding to organic ligands (Wiggenhauser et al., 2016, 2018, 2021). For the latter, it was hypothesized that Cd binding to reduced sulfur groups (R-SH, thiols) in the bacteria *E.coli* to detoxify Cd resulted in an enrichment of light isotope in membranes (Horner et al., 2013). Furthermore, cereals strongly retained light Cd isotopes in roots which lead to an enrichment of heavy isotopes in shoots and grains (Wiggenhauser et al., 2016; Imseng et al., 2019; Wiggenhauser et al., 2021; Zhang et al., 2021). The immobilization of light isotopes was ascribed to binding of Cd to thiols to detoxify and sequester Cd in

roots and shoot parts and to avoid accumulation of Cd in grains (Wiggenhauser et al., 2016). Together, studies in living organisms proposed that sulfur (S) involved detoxification and immobilization processes of Cd could be a major driver of Cd isotope fractionation. However, no isotope fractionation factor for Cd binding to distinct organic ligands exist yet, which makes it difficult to interpret Cd isotope fractionation in complex biological systems.

During the past few years, calculating isotope fractionation for distinct metal complexes has significantly improved metal isotope process tracing applications in complex biogeochemical systems (Fujii and Albarède, 2012; Moynier et al., 2013; Fujii et al., 2014; Wiederhold, 2015; Albarede et al., 2016; Moynier and Fujii, 2017). For inorganic Cd complexes, theoretical calculations predicted that Cd hydroxides and Cd nitrates are isotopically heavier compared to hydrated Cd while hydrated Cd is heavier than Cd chlorides and hydrosulfide (Yang et al., 2015). Guinoiseau et al. (2018) recently verified these in a Cd sulfide precipitation experiment which revealed that Cd light isotope was enriched in sulfide and that the enrichment of light isotope decreased with increasing chloride concentration in solution. For organic ligands, either experimental or theoretical Cd isotope fractionation data of Cd organic complexes has not been studied. Such Cd isotope fractionation data would be particularly useful to improve Cd isotope process in tracing complex biogeochemical systems where organic ligands play a crucial role on the fate of Cd in the environment. Here, we aimed to strengthen Cd isotope process tracing approaches by applying density functional theory (DFT) to calculate Cd hydrated complexes

$\text{Cd}(\text{H}_2\text{O})_4^{2+}$ and $\text{Cd}(\text{H}_2\text{O})_6^{2+}$; Cd-citrate complexes $\text{Cd}(\text{cit})_2^{4-}$, $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$,
 $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$; CdEDTA; Cd-histidine $\text{Cd}(\text{his})_2\text{H}_2\text{O}$; Cd-DMPS
complexes $\text{Cd}(\text{DMPS})_2^{4-}$ and $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$; Cd-cysteine $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$; Cd-
glutathione complex $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$. The obtained results were discussed regarding
its implications for past and future Cd isotope processes tracing approaches.

2. Theory and methods

2.1. Cd organic complexes

Oxygen (O), nitrogen (N), and sulfur (S) are abundant elements that essential for all
living organisms. In organic ligands, they serve as donor atoms to bind metals such as
Cd as part of organic complexes such as citrate (cit) (McLean et al., 2013; Panfili et
al., 2009; Zorrig et al., 2010), histidine (his) (Wierzbicka et al., 2007; Gunawardana et
al., 2010; Hoch et al., 2012; Colaneri et al., 2013), Ethylenediaminetetraacetic acid
(EDTA) (Kovács et al., 2010), cysteine (cys) (Leitenmaier et al., 2011; Cao et al.,
2014; Smith et al., 2015), glutathione (GSH) (Prévéral et al., 2009; Seth et al., 2011;
Wu et al., 2013), and dimercaptopropane sulfonic acid (DMPS) (Zeini Jahromi et al.,
2014). These complexes are involved in controlling uptake, transport, and
sequestration of Cd in living organisms, whereas EDTA and DMPS are model
compounds for strong chelating complexes. EDTA represents chelators with O and N
donors such as nicotianamine (Clemens et al., 2013; Marković et al., 2017;

Puschenreiter et al., 2017) and DMPS represents strong chelators with S donors such as phytochelatin (Marentes and Rauser, 2007; Pal et al., 2019).

2.2. Calculations

Equilibrium isotope exchange reaction between two metal complexes can be represented by:

where Y denotes one element that is represented by light (Y) and heavy isotopes (Y^*). A and B represent two different ligands. Ligands and isotopes of Y form the chemical complexes AY and BY . The isotope fractionation factor α between the complexes AY and BY is defined as:

$$\alpha_{AY-BY} = K_{eq} = \frac{\beta_{AY}}{\beta_{BY}} \quad (2)$$

the isotope fractionation factor is expressed in permill [‰]:

$$10^3 \ln \alpha_{AY-BY} = 10^3 \ln \beta_{AY} - 10^3 \ln \beta_{BY} \quad (3)$$

In these equations, K is the equilibrium constant, which is equal to the α of the isotope exchange reaction of chemical complexes (AY , BY) that exchange the same element (Y). β is the reduced partition function ratio (RPFR). Bigeleisen and Mayer (1947) and Urey (1947) suggested that equilibrium mass-dependent isotope fractionation factors results from the molecular vibrational frequencies. β can be calculated as:

$$\beta_{114-110} = \prod_i \frac{{}^{114}U_i e^{-{}^{114}U_i/2}}{{}^{110}U_i e^{-{}^{110}U_i/2}} \frac{1 - e^{-{}^{110}U_i}}{1 - e^{-{}^{114}U_i}} \quad (4)$$

U_i and v_i are defined as:

$$U_i = hv_i/kT \quad (5)$$

Here, h , k , and T refer to the Planck's constant, Boltzmann constant and absolute temperature, respectively. v_i is the harmonic vibrational frequency of the i th vibrational mode in s^{-1} . The number of vibrational modes for non-linear molecules is $3n-6$ (n is the number of atoms in the molecule), $3n-5$ for linear molecules.

In this study $^{114}\text{Cd}/^{110}\text{Cd}$ isotope ratios were chosen to study the Cd isotope fractionation of Cd partitioning into different chemical complexes. The $^{114}\text{Cd}/^{110}\text{Cd}$ is a widely used isotope ratio in experimental (Rehkämper et al., 2011; Horner et al., 2013; Pallavicini et al., 2014; Chrastný et al., 2015; Wei et al., 2016; Li et al., 2018) and theoretical studies (Yang et al., 2015). Gaussian 09 (Dennington et al., 2009; Frisch et al., 2009) was used to calculate the geometries optimization and vibrational frequencies of Cd species using Becke-style 3-parameter (B3) density functional theory with the Lee-Yang-Parr (LYP) correlation functional (Lee et al., 1988; Becke, 1993a, b). In this study, the mixed basis sets were used, for H, C, N, O, and S, the all-electron basis set 6-311+G(d, p) was used (Clark et al., 1983; Francel et al., 1982; Krishnan et al., 1980; McLean and Chandler, 1980; Spitznagel et al., 1987); for Cd, an effective-core potential (ECP) basis set LanL2DZ was chosen (Hay and Wadt, 1985). The “ultrafine” numerical integration grid was used and the molecular geometries were optimized without any forced symmetry for all complexes. The setting of exchange correlation functionals may have effect on the calculated vibrational frequencies, and four exchange correlation functionals B3LYP, BVP86,

B3PW91 and PBEPBE were tested. For $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$, the mean square errors of the calculated vibrational frequencies of the four exchange correlation functionals are 366.90, 874.94, 1084.19 and 7440.05 respectively (Table S1), the calculated frequencies by B3LYP are more consistent with the experimental results and the B3LYP functional was chosen to estimate the isotope fractionation of Cd complexes in this study.

3. Results and discussion

3.1. Optimized molecular geometries

The optimized geometries of the organic Cd complexes are shown in Fig. 1. For comparison, Table 1 lists the optimized bond lengths calculated by this study, and previously published theoretical and experimental data. Donor atoms, optimized coordinated bond lengths (Å) and mean bond lengths (Å) are shown in Table S3 (Supplementary material). The optimized Cd-O distances of $\text{Cd}(\text{H}_2\text{O})_4^{2+}$ and $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ (Fig. 1a, b) by using the basis set 6-311+G(d, p) are consistent with those by using the basis set 6-31+G(d, p) (Yang et al., 2015).

For Cd-citrate complexes: $\text{Cd}(\text{cit})_2^{4-}$, $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$, $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$, the deprotonated carboxyl groups in Cit^{3-} are always coordinated to the central Cd^{2+} (Bertoli et al., 2015). The d10 electron configuration of Cd^{2+} favors sixfold coordination and forms octahedral geometry (Siddiqui et al., 2011), while in

less bulky ligands, Cd^{2+} tends to form tetrahedral coordination complexes (Ramalho and Figueroa-Villar, 2002; Bertoli et al., 2015). $\text{Cd}(\text{cit})_2^{4-}$ (Fig. 1c) and $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ (Fig. 1d) with fourfold coordination complexes, are adducts of two citrate molecules and have several isomers in solution (Bertoli et al., 2015). They differ in their protonation and each of the two citrate molecules provided two carboxylate oxygen atoms to coordinate to Cd^{2+} . The coordinated bond lengths of $\text{Cd}(\text{cit})_2^{4-}$ and $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ were 2.21, 2.22 Å and 2.14-2.38 Å respectively. The Cd atoms in $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ (Fig. 1e) and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$ (Fig. 1f) were sixfold coordinated, their bond lengths were 2.24-2.40 Å and 2.24-2.43 Å, respectively.

CdEDTA (Fig. 1g) is sixfold coordinated, and EDTA provides two N and four O donor atoms for Cd^{2+} . The stronger binding of Cd^{2+} to N than to O, and the electrostatic attraction induced by the carboxylate result in a high stability for CdEDTA (Kovács et al., 2010; Karak et al., 2016). The calculated Cd-O and Cd-N distances (Cd-O: 2.26, 2.36; Cd-N: 2.48, Table 1b) in this study were close to those calculated by Kovács et al. (2010). Cd-histidine ($\text{Cd}(\text{his})_2\text{H}_2\text{O}$, Fig. 1h) is also sixfold coordinated and contains an imidazole ring, carboxyl and amino groups that provide four N and two O donor atoms for Cd^{2+} (Colaneri et al., 2013). The calculated distances were 2.26 Å for Cd-O 2.41-2.48 Å for Cd-N (Table 1b).

The ligand DMPS contains two thiolate groups and one sulfonate group, and the thiol groups of the DMPS chelate Cd^{2+} in fourfold coordination (Zeini Jahromi et al., 2014, Fig. 1i and 1j). For 1:1 Cd-DMPS complexes, the calculated average distance of Cd to its S donor atoms was 2.48 Å. For 1:2 Cd-DMPS complexes, the average bond

distance to four S donor atoms was 2.69 Å. The calculated bond lengths were consistent with the previously published values (Table 1b) (Zeini Jahromi et al., 2014).

For $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$ (Fig. 1k), the thiol group of cysteine tends to bind the metal ion by S donor atoms when cysteine is present in excess (Jalilehvand et al., 2009; Fujii et al., 2014). In our study, Cd was bound to three water molecules and one thiol group of cysteine, the bond length of Cd to its S donor atoms was 2.48 Å, which was slightly shorter than the experimental data of Cd-cysteine 2.52-2.54 Å (Jalilehvand et al., 2009). Glutathione, γ -Glu-Cys-Gly, is a thiol-containing tripeptide, and the ligands of 1:2 Cd-glutathione complexes (Fig. 1l) are GS^{3-} molecules with amide protons, where Cd has a tetrahedral coordination sphere and the complex primarily involves two deprotonated thiol groups from cysteine residues and two water molecules (Delalande et al., 2010). EXAFS spectra of Cd-glutathione complexes suggested Cd was fourfold coordination and S atoms were identified as the binding atoms at 2.54 ± 0.1 Å (Isaure et al., 2015). The calculated Cd-S mean bond distance in this study was in agreement with previous EXAFS result (2.545 Å) (Table 1b).

3.2. Comparison with experimental vibrational frequencies

Only a few experimentally determined vibrational frequencies exist for organic Cd complexes since they are difficult to determine experimentally. Richet et al. (1977) thought the effects of anharmonicity on the isotope fractionation are expected to be

quite small, here only harmonic vibration was considered. Table 2 lists the calculated harmonic vibrational frequencies of the ^{114}w isotopomer and ^{110}w isotopomer of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ and the experimental data by FTIR (Bertoli et al., 2015). The frequency shifts values $10^3(1 - ^{114}\text{w}/^{110}\text{w})$ of Cd isotopes are also listed.

In Table 2, w_1 is the twisting vibration mode of H-C-H with stretching vibration mode of C-O, the experimental vibrational frequencies by Bertoli et al. (2015) was 1027.05 cm^{-1} , the calculated data by this study were 1041.1681 cm^{-1} for ^{114}w isotopomer and 1041.1686 cm^{-1} for ^{110}w isotopomer, the average value of the calculated frequency of the two isotopomers is about 1.375% higher than experimental data. w_2 is the rocking vibration mode of H-C-H with stretching vibration mode of C-C, the experimental data was 1078.98 cm^{-1} , the calculated frequencies were 1079.978 cm^{-1} for Cd heavy isotope and 1079.9783 cm^{-1} for the light one, the average frequency values by this calculation is 0.093% higher than experimental data. w_3 is the twisting vibration mode of H-C-H with stretching vibration mode of C-C, the calculated average data is 1.041% lower than experimental data. w_4 is the scissoring vibration mode of H-C-H, the average data by calculation is close to the experimental data and the calculated average frequency is 0.490% lower than experimental data. w_5 is the rocking vibration mode of H-C-H with stretching vibration mode of C-C and C-O, the average data by calculation is 0.698% higher than experimental data. w_6 is the wagging vibration mode of H-C-H with scissoring vibration mode of O-H, the frequency difference between experiment and the average theory calculation is 0.142%. The w_7 is the symmetrical stretching vibration and the

difference between calculation and experiment is 0.310%. w_8 is the symmetrical stretching vibration mode of COO^- , the difference of calculated data and experimental data is 0.069%. w_9 is asymmetrical stretching vibration of COO^- , the average frequency calculated is 3.187% higher than experimental results. For w_{10} , it is stretching vibration mode and the calculated result is 0.652% lower than experimental data (Table 2). Overall, the calculated frequencies were generally consistent with previously experimental data of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$.

The accuracy of vibrational frequencies can be further propagated in the final $10^3\ln\beta$ values (Schauble et al., 2003, 2004; Schauble et al., 2007). Frequency scaling factors can often be used to correct the calculated vibrational frequencies which are able to reproduce the experimental frequencies. However, the simple harmonic frequency calculated by quantum chemistry methods need to be corrected when it is used to calculate isotope fractionation involving larger molecules (Liu et al., 2010; Fujii et al., 2014). Here frequency scaling factors were not needed in this study.

3.3. Reduced partition function ratios, $10^3\ln(\beta_{114-110})$ for Cd complexes

In nature, mass-independent Cd isotope effects may not be significant and mass dependent effects are the main factor for naturally occurring Cd isotope variations (Rehkämper et al., 2011). Here, only the mass-dependent isotope effects for various Cd species have been studied. The calculated reduced partition function ratios $10^3\ln(\beta_{114-110})$ of the Cd complexes with varying temperatures from 0 °C to 100 °C

calculated in this study are reported in Table 3. ^{114}Cd and ^{110}Cd have the largest mass difference among Cd isotopes (Carignan et al., 2004; Wombacher and Rehkämper, 2004), usually $^{114}\text{Cd}/^{110}\text{Cd}$ isotope ratios were chosen to study the Cd isotope fractionation of Cd partitioning into different chemical complexes. Mass-dependent isotope fractionation is a function of temperature (T), and can be expressed as below:

$$10^3 \ln(\beta_{114-110}) = A \times \frac{10^6}{T^2} + B \quad (6)$$

Where A , B are the regression parameters, which can be figured out from Table 3. The A , B values of these complexes are listed in Table S2, for comparison their relationship also be figured in Fig. 2. Our calculation shows that the $10^3 \ln \beta$ of $^{114}\text{Cd}/^{110}\text{Cd}$ for these complexes decreases in the order of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^- > \text{Cd}(\text{cit})(\text{H}_2\text{O})_3^- > \text{CdH}(\text{cit})(\text{H}_2\text{O})_4 > \text{CdEDTA} > \text{Cd}(\text{his})_2\text{H}_2\text{O} > \text{Cd}(\text{cit})_2^{4-} \approx \text{Cd}(\text{H}_2\text{O})_6^{2+} > \text{Cd}(\text{H}_2\text{O})_4^{2+} > \text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+} > \text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-} > \text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^- > \text{Cd}(\text{DMPS})_2^{4-}$ at $0 \sim 100^\circ\text{C}$.

Previous studies demonstrated that the types of donor atoms (O, N, S) of organic ligands are a main driver for Zn isotope fractionation (Albarède et al., 2011; Fujii and Albarède, 2012; Balter et al., 2013; Moynier et al., 2013; Fujii et al., 2014). Particularly, O donors preferentially bind heavier Zn isotopes than S donors. Cd and Zn are in the same group in the periodic table which means that the two elements have the same number of electrons in their outer valence shell. Thus, the elements share similar chemical properties such as a flexible coordination chemistry, they are non-redox sensitive, and have similar stability constants (John et al., 2017; Maret and Moulis, 2013; Sóvágó and Várnagy, 2013). It is likely that O, N, and S donor atoms

may have a similar effect on Cd isotope fractionation as they do for Zn. This hypothesis has been recently partly verified by Yang et al. (2015) who reported an enrichment of heavy Cd isotopes for O and N compared to S donors of inorganic ligands. In addition, studies on Zn isotopes have shown that the number of coordination for the same donor atoms can also determine isotope fractionation (Fujii et al., 2014). For instance, fourfold coordinated Zn-amino acid complexes had larger $10^3\ln(\beta_{114-110})$ values than the sixfold coordinated complexes of the same amino acid. The relationship between the $10^3\ln(\beta_{114-110})$ values and donor atoms type of the Cd complexes at 25°C is given in Fig. 3 (the types and numbers of donor atoms are given in Table S3). For Cd complexes, S or combinations of S and O donor atoms tended to complex with lighter Cd isotopes. Furthermore, the $10^3\ln(\beta_{114-110})$ disparities induced by S and S/O donor atoms were bigger than those by O and O/N donor atoms. The relationship between $10^3\ln(\beta_{114-110})$ and mean bond lengths of Cd to its donor atoms at 25°C was shown in Fig. 4. Overall, mean coordinated bond lengths of complexes with O donor atoms were shorter than those with S donor atoms, except $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$. The reason may be that $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$ has three O donors and one S donor.

Among all studied Cd complexes, $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ has the largest $10^3\ln(\beta_{114-110})$ values while $\text{Cd}(\text{DMPS})_2^{4-}$ has the smallest $10^3\ln(\beta_{114-110})$ values (Fig. 2 and Table 3), their difference can reach 1.18 at 25°C. Cd-citrate complexes can be fourfold coordinated ($\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ and $\text{Cd}(\text{cit})_2^{4-}$) and sixfold coordinated ($\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$), and their $10^3\ln(\beta_{114-110})$ values can differ up to 0.213 at 25°C which means that the structure difference of these Cd-citrate complexes can result in

337 Cd isotope fractionation (Fig. 1, 2). In addition, $10^3\ln(\beta_{114-110})$ values of fourfold
 338 coordinated $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ were larger than those of sixfold coordinated
 339 $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$, but those of $\text{Cd}(\text{cit})_2^{4-}$ are smaller than those of
 340 $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$. Thus, for Cd-citrate complexes, the coordination
 341 number is only one of the factors that have an effect on Cd isotope fractionation,
 342 when estimating Cd isotope fractionation of them, other factors should be considered.

343 The Cd-cysteine, Cd-GSH, and Cd-DMPS complexes contain S donor atoms. Our
 344 calculations revealed that these Cd complexes had lower $10^3\ln(\beta_{114-110})$ values in
 345 comparison with hydrated Cd complexes and organic Cd complexes that contained O
 346 and N donor atoms (Table 3 and Fig. 3). The lower $10^3\ln(\beta_{114-110})$ values in S
 347 containing ligands is in agreement with previous studies that reported $10^3\ln\beta$ values
 348 for inorganic Cd (Yang et al., 2015) and organic Zn complexes (Fujii et al., 2014).
 349 Among the complexes that contained S and O donor atoms in this study, their
 350 $10^3\ln(\beta_{114-110})$ values slightly differed. For instance, $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$ and
 351 $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$ were complexed with two S donor atoms from the organic
 352 molecules and two O donor atoms from water molecules. The average bond lengths of
 353 Cd-S in $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$ (2.48 Å) was shorter than that in $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$ (2.545
 354 Å, Table 1 and S3). The average Cd-O bond lengths in $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$ (2.95 Å)
 355 were longer than that of $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$ (2.415 Å). Our data suggests that chelators
 356 with S ligands significantly change the bond lengths between Cd and other donor
 357 atoms than S which might contribute to the lower $10^3\ln(\beta_{114-110})$ value in the chelating
 358 $\text{Cd}(\text{DMPS})_2^{4-}$ complex.

As anticipated, the $10^3\ln(\beta_{114-110})$ values of $\text{Cd}(\text{DMPS})_2^{4-}$, a Cd chelating complex with four S and no O donor atoms, was smaller compared to $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$ (Table 3 and Fig. 3). This observation agrees with previously published calculations of Zn sulfides where the smallest fractionation occurred in Zn sulfide complexes with four S donor atoms compared to Zn sulfide complexes contained mixtures of S and O donor atoms (Fujii et al., 2011). Together, our data suggests that a large shift towards light isotopes occurs when Cd is complexed to a chelating organic ligand with two or four S donor atoms when compared non-chelating S donor atoms and O/N donor atoms in general.

Experimentally obtained isotope fractionation factors for Zn (Marković et al., 2017) and Cu (Ryan et al., 2014) complexes reported a direct relation between the stability of complexes and the extent and isotope fractionation factors. This relation was also observed in our data, however, the difference of $10^3\ln(\beta_{114-110})$ values between metal chelator CdEDTA and $\text{Cd}(\text{his})_2\text{H}_2\text{O}$ was comparably small (0.027 at 25°C, Fig. 2 and Table 3). Though CdEDTA forms more stable complexes than Cd-histidine complexes (Sóvágó and Várnagy, 2013; Karak et al., 2016), the coordination number was six for both complexes while the CdEDTA had four O and two N donor atoms and $\text{Cd}(\text{his})_2\text{H}_2\text{O}$ had four N and two O donor atoms, and the average bond lengths between the central Cd atom and its donor atoms were very similar: CdEDTA 2.367 Å (Cd-O: 2.26, 2.36 Å; Cd-N: 2.48 Å); $\text{Cd}(\text{his})_2\text{H}_2\text{O}$ 2.378 Å (Cd-O: 2.26 Å; Cd-N: 2.41-2.48 Å, Table S3 and Fig. 4). Hence, the small differences in Cd isotope fractionation between the two complexes might have been demonstrated by the

distinct coordination and bond lengths of the two complexes.

3.4. Error analysis for Cd isotope fractionation

Vacuo and solvation models can cause isotope fractionation factors inaccuracies (Hill and Schauble, 2008; Yang et al., 2015). In ideal vacuum gaseous conditions, the influence of the surrounding environment such as solvents on the solute molecules in the real system is ignored. To overcome this limitation, some solvent models were established to simulate the effects of solvents on solutes. The polarized continuum models (PCMs) are widely used to simulate the aqueous environment (Tomasi et al., 2005; Tsipis, 2014). However, Yang et al. (2015) found that the bond lengths optimized by IEFPCM model are larger than those by vacuo model and the $10^3\ln(\beta_{114-110})$ results calculated in the IEFPCM model are smaller than those in vacuo model, and thought that the optimized structures and $\ln\beta$ values of Cd complexes calculated in vacuo are more consistent with the experimental data. For comparison, the implicit solvation models IEFPCM (the integral-equation-formalism versions of PCM) and CPCM (conductor-like PCM) were used to calculate the optimized molecular structures and $10^3\ln(\beta_{114-110})$ at 25°C for studied complexes (Table S4 and S5), as well as the model of $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ with second hydration sphere $\text{Cd}(\text{H}_2\text{O})_{18}^{2+}$ (Table S6). Our calculation showed that most of the bond lengths optimized in solution by this study were larger than those in vacuum (Table S4). This was agreement with the results of inorganic Cd complexes (Yang et al., 2015). For $10^3\ln(\beta_{114-110})$ values, not

only does difference exist between two implicit models and vacuum model but also between two implicit models. By comparing with vacuum model, IEFPCM and CPCM solvation models decrease the $10^3\ln\beta$ of $\text{Cd}(\text{H}_2\text{O})_4^{2+}$ by 0.346 and 0.221 at 25°C respectively, and increase the $10^3\ln\beta$ of $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ by 0.139 and 0.166 at 25°C respectively. For $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$, $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$, $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$ and $\text{Cd}(\text{his})_2\text{H}_2\text{O}$, IEFPCM and CPCM model decrease the $10^3\ln\beta$ by 0.175-0.580 and 0.206-0.567 and increase the $10^3\ln\beta$ of $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$ by 0.281 and 0.401 at 25°C respectively. For $\text{Cd}(\text{cit})_2^{4-}$, CdEDTA , $\text{Cd}(\text{DMPS})_2^{4-}$, these two models increase the $10^3\ln\beta$ by less than 0.1 at 25°C. For $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$, the IEFPCM solvation model decrease the $10^3\ln\beta$ by 0.109 and CPCM model increase the $10^3\ln\beta$ by less than 0.1 at 25°C, the implicit solvation models have different effects on Cd isotope fractionation (Table S5). The main reason may be that the simple harmonic vibrational frequencies have been polluted by translation and rotation which make the inaccurate for frequencies data in solvation models (Yang et al., 2015), and the levels of “pollution” may be different for different Cd complexes.

Setting the second hydration sphere is able to make the calculated frequencies closer to the experimental values and improve the $10^3\ln\beta$ for Ni and Zn (Fujii et al., 2014), the same phenomenon may occur in Cd hydrate species. Our calculation showed that for $\text{Cd}(\text{H}_2\text{O})_6^{2+}$, the $10^3\ln\beta$ values for the explicit model as $\text{Cd}(\text{H}_2\text{O})_{18}^{2+}$ is 2.377 and 1.990, 1.923 for explicit model + IEFPCM and explicit model + CPCM at 25°C respectively. Compared with the vacuum model, the explicit model increases the $10^3\ln\beta$ values and explicit + implicit model decrease them (Table S6). The total

symmetric stretching mode of hexaaqua complexes, ν_1 CdO_6 , is shown in Table S6. The calculated ν_1 frequency values of large cluster $\text{Cd}(\text{H}_2\text{O})_{18}^{2+}$, $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ + IEFPCM and $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ + CPCM are closer to previous calculation and experimental data than that of $\text{Cd}(\text{H}_2\text{O})_6^{2+}$ (Table S6), which means solvation models make the frequency values closer the literature values and the solvent effect on $10^3\ln\beta$ values are needed to be considered.

Frequency is another most frequently mentioned factor that may cause uncertainties or errors of the calculated reduced partition function ratios (Schauble et al., 2003, 2004; Schauble et al., 2007; Méheut et al., 2007, 2009; Weeks et al., 2007; Yang et al., 2015). For lack of experimental vibrational frequency of Cd organic complexes, it is impossible to evaluate the RPFR errors for them, and different vibration frequencies may lead to discrepant uncertainty in $10^3\ln(\beta_{114-110})$ values at 25 $^\circ\text{C}$ (Vogt et al., 1993; Schauble, 2007; Yang et al., 2015). Based on existing experimental frequency data of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$ and this calculation, the maximum difference between them is 3.187%, and the average deviation is about 0.293%. Based on Schauble (2007, 2011), calculated frequencies may lead to an error of less than 0.6% for $10^3\ln(\beta_{114-110})$ values of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$.

3.5 Implications for Cd process tracing applications in biogeochemistry, supergene geochemistry and environmental science

Metal isotope fractionation can be used to trace processes that control the

distribution of an element in terrestrial and aquatic environments. Previous experimental studies hypothesized that the Cd isotope fractionation is strongly linked to Cd speciation to organic ligands with S donor atoms to detoxify and immobilize Cd in living organisms (Horner et al., 2013; Wiggenhauser et al., 2016, 2021; Imseng et al., 2019). Results by this study and Yang et al. (2015) revealed that an enrichment of light isotopes occurs in thiol ligands when compared to hydrated Cd and Cd bound to O/N donor atoms of organic ligands, which will strengthen not only Cd isotopes as a process tracing tool, but also the understanding of Cd isotope cycling in aquatic and terrestrial systems. For example, to reduce inputs of the toxic trace metal Cd into the food chain of humans and animals, processes that control the mobility of Cd in terrestrial and aquatic environments need to be well understood. The results that heavy Cd isotopes preferably bind to oxygen and nitrogen donor atoms while light Cd isotopes bind to sulfur donor atoms of organic ligands compared to hydrated Cd²⁺ provides information on processes on the immobilization of Cd isotopes in living organisms which are related to Cd detoxification processes with sulfur.

Furthermore, the strongest Cd isotope fractionation compared to hydrated Cd occurred in chelating S donor ligands, particularly in a chelating S donor ligand in which Cd is exclusively bound to S. Thus, our data confirms the hypothesis that the retention of light isotopes in roots and shoots of grasses (Wiggenhauser et al., 2016, 2021; Imseng et al., 2019) and membranes of *E.Coli* (Horner et al., 2013) could be induced by the immobilization of light Cd isotopes through strong Cd binding to chelators with S donor atoms such as phytochelatins (Clemens et al. 2019). This

chelation would retain light Cd isotopes e.g., in the roots of cereals, while other chemical Cd species such as hydrated Cd that are enriched in heavy isotopes can be transported by membrane proteins towards the shoot. The Cd isotope fractionation induced by chelating thiols may have implications on Cd isotope fractionation in other plants than grasses. Cd hyperaccumulator plants can cope with high Cd concentrations and store, unlike cereals, the majority of the Cd taken up from soils in their shoots (Zhou et al. 2020). To cope with the high Cd shoot concentrations, Cd is mostly bound to O donor atoms of e.g., organic acids and to a lesser extent to S donors (Tian et al. 2011; Isaure et al. 2015). Based on our findings, the Cd isotope fractionation in Cd accumulating plants could potentially provide novel insights into the role of Cd binding to different donor atoms on the translocation of Cd within the shoot. Recent studies focused on Cd isotope fractionation in cacao since cacao beans often exceed the threshold values for Cd potentially leading to elevated Cd concentrations in chocolate (Moore et al. 2020; Barraza et al. 2019). Similar to grasses such as wheat, rice, and barley, cacao seems to retain Cd and its light isotopes in the roots (Moore et al. 2020). Our findings suggest that Cd binding to thiols may play also a crucial role to retain Cd in roots of cacao and thereby limit the Cd transport into cacao beans.

Our results further suggest that Cd ligands, especially thiols, may play a key role in Cd isotope fractionation in living organisms, soils, and waters. In this study, the Cd isotope fractionation between hydrated Cd and Cd chelated by S donor atoms was ~ 1‰. The largest Cd isotope fractionation that has been observed between roots and shoots of plants that strongly retain light Cd isotopes in roots was around 0.60 ‰

(Wiggenhauser et al. 2016, 2021; Imseng et al. 2018; Moore et al. 2020). The difference between our results and the experimentally determined Cd isotopes fractionation between root and shoots may be caused by additional isotope effects that complement isotope effects at equilibrium. The transfer from root to shoot includes membrane transport (Deng et al. 2019). This transport requires fast binding of Cd to a metal binding site of a membrane protein prior to unidirectional membrane transport (Wang et al., 2014; Zhao et al., 2016). Thus, membrane transport might be at least partly kinetically controlled (Köbberich and Vance, 2017). Kinetically controlled processes favor light isotopes through their faster reaction rates (Wiederhold, 2015) while type of metal binding sites of a membrane transporters (e.g., cysteine, histidine) might play an additional role for isotope fractionation during membrane transport. Together, our results suggest that equilibrium Cd isotope fractionation in plants induced by binding of Cd to organic molecules occur in parallel to kinetic isotope effects.

In soils, sediments, and water, organic matter poses an important binding site for Cd and partly controls the mobility of Cd. For instance, soil organic matter derives from decomposed biomass and provides a mixture of O, N, and S donor atoms for Cd in the solid and liquid phase of the soil (Karlsson et al., 2007; Tiberg et al., 2018). Besides processes such as Cd sulfide precipitation and Cd uptake into phytoplankton, soluble organic ligands might significantly control the Cd distribution in water columns and sediments during the oceanic Cd cycle (Guinoiseau et al., 2018). Our data implies that Cd sorption of Cd to organic matter can enrich or deplete the

hydrated Cd pool in heavy and could provide further insights into the role of specific binding sites of organic matter on Cd cycling in the environment.

4. Conclusion

This study provides a first prediction that describes Cd equilibrium isotope fractionation induced by Cd complexation to organic ligands. The $10^3 \ln \beta$ of $^{114}\text{Cd}/^{110}\text{Cd}$ for these investigated complexes decreased in the order of $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^- > \text{Cd}(\text{cit})(\text{H}_2\text{O})_3^- > \text{CdH}(\text{cit})(\text{H}_2\text{O})_4 > \text{CdEDTA} > \text{Cd}(\text{his})_2\text{H}_2\text{O} > \text{Cd}(\text{cit})_2^{4-} \approx \text{Cd}(\text{H}_2\text{O})_6^{2+} > \text{Cd}(\text{H}_2\text{O})_4^{2+} > \text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+} > \text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-} > \text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^- > \text{Cd}(\text{DMPS})_2^{4-}$ at $0 \sim 100^\circ\text{C}$. The sequence reveals that Cd complexation to organic ligands with O and N donor atoms are enriched in heavy isotopes while to organic ligands with S donor atoms are enriched with light isotopes. These results provide important information to advance Cd isotopes as a process tracing tool in complex biological systems and further improve the understanding of Cd isotope cycling in aquatic and terrestrial systems.

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Appendices. Supplementary material

Table S1: Comparing the experimental vibrational frequencies with calculated results ($^{110}\omega$) employed by four different exchange correlation functionals for Cd(Hcit)(H₂cit)⁻. Table S2: The fitting factors A, B for $10^3\ln(\beta_{114-110})=A\times 10^6/T^2+B$ (T is K). Table S3: The donor atoms, coordinated bond lengths (Å) and mean bond lengths (Å) for Cd complexes. Table S4a: Optimized bond lengths (Å) of the Cd hydration complexes and citrate complexes calculated with solvation models. Table S4b: Optimized bond lengths (Å) of the organic Cd complexes calculated with solvation models. Table S5: The $10^3\ln(\beta_{114-110})$ of Cd complexes calculated in vacuo and solvation models (IEFPCM, CPCM) at 25°C. Table S6: The vibrational frequencies ($^{110}\omega$) and $10^3\ln\beta$ values of Cd(H₂O)₆²⁺ and Cd(H₂O)₁₈²⁺.

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Figure Captions:

Fig. 1. Optimized molecular structures for various Cd species. a-b: Cd hydrate; c-f: Cd-citrate, the original source of the structure derives from Bertoli et al. (2015) and Fujii et al. (2012); g: CdEDTA (Kovács et al., 2010); h: Cd-histidine (Colaneri et al., 2013); i-j: Cd-DMPS (Zeini Jahromi et al., 2014); k: Cd-cysteine (Jalilehvand et al., 2009 and Fujii et al., 2014); l: Cd-glutathione (Delalande et al., 2010). Abbreviations are cit (citrate), EDTA (ethylenediaminetetraacetic acid), his (histidine), DMPS (dimercaptopropane sulfonic acid), cys (cysteine), and deprotonated glutathione (GSH) is shown as GS. Symbol keys: H (white), C (grey), N (blue), O (red), S (purple), Cd (yellow).

Fig. 2. Temperature dependence of $10^3 \ln(\beta_{114-110})$ for Cd hydrate, citrate, EDTA, histidine, DMPS, cysteine and glutathione complexes. X-axis shows the function of $10^6/T^2$ (lower shaft) and corresponding temperature (upper shaft, 0-100 K), Y-axis shows the $10^3 \ln(\beta_{114-110})$ values.

Fig. 3. Cd ($^{114}\text{Cd}/^{110}\text{Cd}$) isotopic variations with different donor atoms at 25°C. The complexes with O donor atoms are shown as $\square$; N,O donor complexes as Δ ; S,O donor complexes as $\square$; S donor complexes as $\circ$. For O donor complexes, the order of $10^3 \ln(\beta_{114-110})$ values at 25°C from small to large is $\text{Cd}(\text{H}_2\text{O})_4^{2+} < \text{Cd}(\text{H}_2\text{O})_6^{2+} \approx \text{Cd}(\text{cit})_2^{4-} < \text{CdH}(\text{cit})(\text{H}_2\text{O})_4 < \text{Cd}(\text{cit})(\text{H}_2\text{O})_3^- < \text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$; For N,O donor complexes, the order is $\text{Cd}(\text{his})_2\text{H}_2\text{O} < \text{CdEDTA}$; For S,O donor complexes, the order is $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^- < \text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-} < \text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$; The S donor complex is $\text{Cd}(\text{DMPS})_2^{4-}$.

Fig. 4. Reduced partition function ratios, $10^3 \ln(\beta_{114-110})$ vs. mean bond length (Å) at 25°C. Just as Fig. 3, the complexes with O donor atoms are shown as $\square$, including $\text{Cd}(\text{H}_2\text{O})_4^{2+}$, $\text{Cd}(\text{H}_2\text{O})_6^{2+}$,

952 $\text{Cd}(\text{cit})_2^{4-}$, $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$, $\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$ and $\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$; N,O donor complexes as Δ ,
 953 including CdEDTA and $\text{Cd}(\text{his})_2\text{H}_2\text{O}$; S,O donor complexes as $\square$, including $\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$,
 954 $\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$ and $\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$; S donor complex as $\circ$, is $\text{Cd}(\text{DMPS})_2^{4-}$.

955

Table 1a Optimized bond lengths (Å) of the Cd hydration complexes and citrate complexes.

	$\text{Cd}(\text{H}_2\text{O})_4^{2+}$	$\text{Cd}(\text{H}_2\text{O})_6^{2+}$	$\text{Cd}(\text{cit})_2^{4-}$	$\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$	$\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$	$\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$
Cd-O	2.24	2.33	2.22,2.21	2.20,2.14, 2.14,2.38	2.24,2.31,2.31, 2.37,2.34,2.40	2.24,2.28,2.29, 2.43,2.42,2.35
	2.24 ^a	2.33 ^a	2.34-2.37 ^b			

^a Yang et al., 2015

^b Bertoli et al., 2015

Table 1b Optimized bond lengths (Å) of the organic Cd complexes.

	CdEDTA	$\text{Cd}(\text{his})_2\text{H}_2\text{O}$	$\text{Cd}(\text{DMPS})_2^{4-}$	$\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$	$\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$	$\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$
Cd-O	2.26,2.36	2.26		2.39,3.51	2.33,2.32,2.32	2.29,2.54
	2.24,2.40 ^a	2.48 ^b		2.39 ^c		
Cd-N	2.48	2.41,2.45, 2.41,2.48				
	2.46 ^a	2.287,2.29 ^b				
Cd-S			2.70,2.68, 2.67,2.71	2.51,2.45	2.48	2.51,2.58
			2.57 ^c	2.48 ^c	2.52-2.54 ^d	2.53-2.55 ^e

^a Kovács et al., 2010

^b Colaneri et al., 2013

^c Zeini Jahromi et al., 2014

^d Jalilehvand et al., 2009

^e Isaure et al., 2015

Table 2 Comparing the experimental vibrational frequencies with calculated results for $\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$.

w/cm^{-1}	Vibration Modes	$\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$			
		EXP ^a	$^{114}_w$	$^{110}_w$	$10^3(1-^{114}_w/^{110}_w)$
w_1	$\tau(\text{HCH}) + \nu(\text{CO})$	1027.05	1041.1681	1041.1686	0.0005
w_2	$\rho(\text{HCH}) + \nu(\text{CC})$	1078.98	1079.978	1079.9783	0.0003
w_3	$\tau(\text{HCH}) + \nu(\text{CC})$	1095.98	1084.5717	1084.5721	0.0004
w_4	$\delta_{\text{sciss}}(\text{HCH})$	1207.78	1201.8587	1201.8594	0.0006
w_5	$\rho(\text{HCH}) + \nu(\text{CC}) + \nu(\text{CO})$	1248.26	1256.977	1256.9772	0.0002
w_6	$\omega(\text{HCH}) + \delta(\text{OH})$	1280.53	1282.3539	1282.3541	0.0002
w_7	ν_s	1391.44	1387.1308	1387.1311	0.0002
w_8	$\nu_s(\text{COO}^-)$	1445.87	1444.8795	1444.8795	0.0000
w_9	$\nu_{\text{as}}(\text{COO}^-)$	1638.70	1690.9311	1690.9322	0.0007
w_{10}	$\nu(\text{OH})$	3350.46	3328.6313	3328.6316	0.0001

δ : scissoring vibration; ρ : rocking vibration; ω : wagging vibration; τ : twisting vibration; ν_s : symmetrical stretching vibration; ν_{as} : asymmetrical stretching vibration.

^a Experimental data obtained for Cd (not Cd isotope specific) by Bertoli et al. (2015).

Table 3 Calculated $10^3 \ln(\beta_{114-110})$ for Cd complexes from 0 to 100 °C.

T(°C)	0	10	25	40	50	100
$\text{Cd}(\text{H}_2\text{O})_4^{2+}$	2.537	2.370	2.148 ± 0.0046	1.956	1.841	1.395
$\text{Cd}(\text{H}_2\text{O})_6^{2+}$	2.711	2.530	2.292 ± 0.0039	2.085	1.962	1.484
$\text{Cd}(\text{cit})_2^{4-}$	2.715	2.533	2.292 ± 0.0029	2.084	1.961	1.481
$\text{Cd}(\text{Hcit})(\text{H}_2\text{cit})^-$	2.961	2.765	2.505 ± 0.0039	2.280	2.147	1.626
$\text{CdH}(\text{cit})(\text{H}_2\text{O})_4$	2.871	2.681	2.429 ± 0.0038	2.211	2.081	1.576
$\text{Cd}(\text{cit})(\text{H}_2\text{O})_3^-$	2.943	2.749	2.491 ± 0.0046	2.268	2.135	1.618
CdEDTA	2.811	2.621	2.371 ± 0.0026	2.155	2.026	1.529
$\text{Cd}(\text{his})_2\text{H}_2\text{O}$	2.777	2.590	2.344 ± 0.0027	2.131	2.005	1.514
$\text{Cd}(\text{DMPS})_2^{4-}$	1.575	1.467	1.325 ± 0.0011	1.203	1.130	0.850
$\text{Cd}(\text{DMPS})(\text{H}_2\text{O})_2^-$	2.086	1.946	1.761 ± 0.0022	1.601	1.506	1.138
$\text{Cd}(\text{cys})(\text{H}_2\text{O})_3^{2+}$	2.233	2.084	1.887 ± 0.0026	1.716	1.614	1.220
$\text{Cd}(\text{GS})_2(\text{H}_2\text{O})_2^{2-}$	2.130	1.987	1.799 ± 0.0025	1.635	1.539	1.162

Highlights:

The isotope fractionation order of selected Cd organic complexes was given.

Compared to hydrated Cd, organic complexes with O and N donors enrich heavier Cd isotopes, complexes with S donors enrich lighter isotopes.

Organic ligands with S donors: chelating ligands were enriched in light isotope compared to non-chelating ligands.

$\text{Cd}(\text{H}_2\text{O})_6^{2+}$ is enriched in heavy isotope compared to $\text{Cd}(\text{H}_2\text{O})_4^{2+}$.