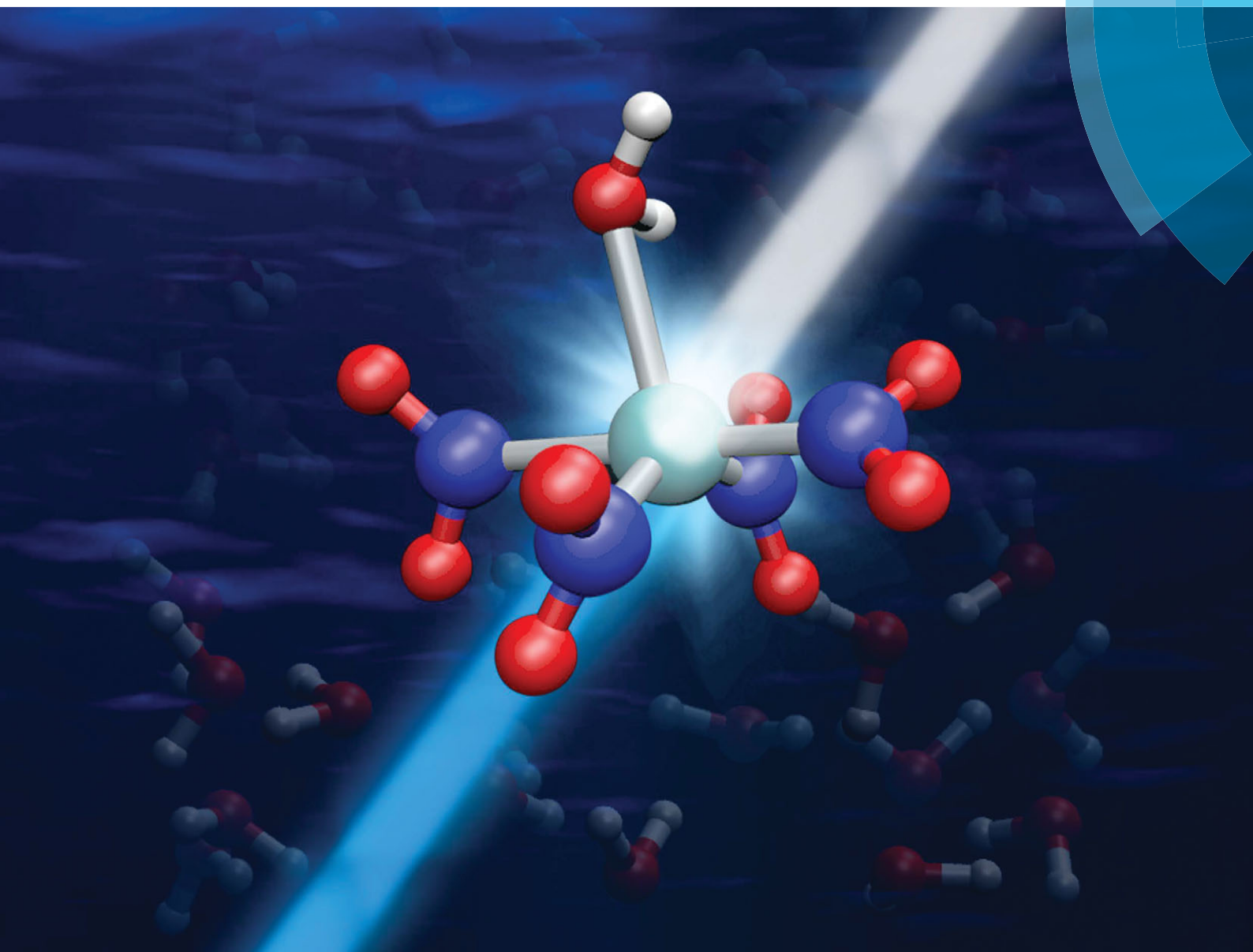


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Origins of optical absorption characteristics of Cu^{2+} complexes in aqueous solutions



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Origins of optical absorption characteristics of Cu^{2+} complexes in aqueous solutions†

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Many transition metal complexes exhibit infrared or visible optical absorption arising from d–d transitions that are the key to functionality in technological applications and biological processes. The observed spectral characteristics of the absorption spectra depend on several underlying physical parameters whose relative contributions are still not fully understood. Although conventional arguments based on ligand-field theory can be invoked to rationalize the peak absorption energy, they cannot describe the detailed features of the observed spectral profile such as the spectral width and shape, or unexpected correlations between the oscillator strength and absorption peak position. Here, we combine experimental observations with first-principles simulations to investigate origins of the absorption spectral profile in model systems of aqueous Cu^{2+} ions with Cl^- , Br^- , NO_2^- and CH_3CO_2^- ligands. The ligand identity and concentration, fine structure in the electronic d-orbitals of Cu^{2+} , complex geometry, and solvation environment are all found to play key roles in determining the spectral profile. Moreover, similar physiochemical origins of these factors lead to interesting and unexpected correlations in spectral features. The results provide important insights into the underlying mechanisms of the observed spectral features and offer a framework for advancing the ability of theoretical models to predict and interpret the behavior of such systems.

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Introduction

Transition metal ion complexes form the basis of coordination chemistry,¹ and are key ingredients in various natural and synthetic systems of interest. For many complexes, a particularly useful aspect is their intrinsic optical absorption, which arises from the existence of partially filled d orbitals. For isolated ions, the five d orbitals are degenerate, but this degeneracy is removed when the ion is placed in a host environment. The rearrangement or the splitting of the energies of the d orbitals strongly depends on the coordination geometry and the chemical nature of the host material. The removal of the degeneracy also enables symmetry-forbidden d–d transitions, which are typically at energies corresponding to transitions in the visible (Vis) or near infrared (NIR).² Unfortunately, the exact relationship between the spectral profile and the local structural, chemical, and environmental factors that give rise to it is not always well understood, making proper interpretation of specific

spectral features very challenging. Addressing these difficulties could in principle enable molecular engineering to obtain a desired optical absorption profile, accelerating the design and development of optical materials with tailored optical properties across a wide variety of applications.

A number of parameters need to be considered for describing the optical characteristics of transition-metal complexes, as well as for revealing their probable configuration in biological settings.³ These include the peak position, intensity, and the spectral width of the absorption band. Ligand-field theory has often been invoked to explain trends in the d–d separation arising from different chemical environments, which in turn determine the peak absorption wavelength (or energy) according to the spectrochemical series.⁴ Notions of ligand-field theory have also been extended to explain experimental observations of optical absorption spectra with successive levels of ligand substitution. For instance, Billo⁵ extended notions of ligand field theory to show that the peak absorption wavelength of ligand-substituted Cu^{2+} complexes follows a linear combination of ligand field strengths of the constituent equatorial ligands. A very similar observation was made by Sigel and Martin,⁶ and later generalized by Prenesti *et al.* to a wider variety of ligands.⁷ Cu^{2+} complexes are extremely important as industrial colorants,^{8,9} and are crucial to the functionality of a variety of biological systems and processes.^{3,10} As an added advantage, Cu^{2+} has only one half-filled electronic

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orbital ($[\text{Ar}] 3d^9$). This simplifies the description because possible transitions between multi-reference spin states can be ignored; *viz.*, a Tanabe–Sugano diagram needs not be used.¹¹ Notably, the universality of the observed correlations in Cu^{2+} complexes suggests there are similarities in the fundamental physics and chemistry that govern the experimentally observed spectroscopic trends with ligand substitution.

Nevertheless, much about the underlying physiochemical motivations for the observations of the peak absorption wavelength of ligand-substituted Cu^{2+} complexes remains unclear. Moreover, trends and structure–property correlations associated with other factors in the peak profile, such as oscillator strength and spectral line width, have not been widely discussed. In practice, the spectral profile is highly sensitive to perturbations within both the colorant complex and the surrounding environment (*i.e.*, solvent),^{4,12,13} which further alter the electronic states associated with the optical transitions (see schematic in Fig. 1). The contributing physical properties are therefore convoluted and interdependent, making them difficult to isolate experimentally when extracting structure–property relationships directly from optical spectra.

In this work we build upon previous studies^{4–7,12–15} to address these shortcomings in our understanding of the optical behavior of Cu^{2+} complexes. Specifically, we present an integrated experimental and theoretical approach that transcends conventional ligand-field theory interpretations to explore the physiochemical origins of the optical absorption profile of aqueous Cu^{2+} complexes in the Vis-NIR range, where the d–d transitions are observed. The approach combines optical (Ultraviolet-Visible-Near Infrared, UV-Vis-NIR) spectroscopy with first-principles molecular dynamics (FPMD) and time-dependent density functional theory (TDDFT).¹⁶ Rather than surveying a broad range of ligands as was done by previous authors,^{5–7,14} our goal is to obtain deeper understanding using model Cu^{2+} complexes with a few representative strong and weak ligands. Four model ligands are investigated: Br^- , Cl^- ,

NO_2^- , and acetate (Ac^-), in addition to the aqua complex. Each is a small, monovalent ion complex that demonstrates monodentate coordination with dilute concentrations of Cu^{2+} ions.^{17–19} This facilitates direct comparisons without introducing additional confounding factors related to steric- or charge-related differences. Based on the reported spectrochemical series^{2,4} which establishes the order of ligand field strength for common ligands, Br^- and Cl^- are classified as weaker ligands than water, whereas Ac^- and NO_2^- are stronger ligands. Recall that the ligand strength does not refer to the strength of the Cu–ligand bond, but rather the effect of ligand substitution on the spectral features: weak ligand substitution (*e.g.*, Br^- and Cl^-) leads to absorption centered at longer wavelengths (lower energies), whereas exchanging with strong ligands (*e.g.*, Ac^- and NO_2^-) leads to absorption at shorter wavelengths (higher energies) with respect to the pure aqua complex.²

As shown below, the absorption spectral profile of the Cu^{2+} –ligand complexes cannot be explained by ligand-field theory alone, but rather reflect a number of factors related to the ligand identity and concentration, fine structure in the electronic states, complex geometry, and solvation environment. In several cases, interesting and unexpected correlations emerge, which are traceable to similar physiochemical origins in the spectral features.

Results

Fig. 2 and 3 show the dependence of the optical absorption spectra in the 1.0–2.3 eV range (Vis-NIR) on ligand concentration for weak (Fig. 2) and strong (Fig. 3) ligands. Focusing first on the energy of maximum absorption within this range, it is observed that weak ligands (Br^- and Cl^-) lead to absorption at lower energies than that for the pure Cu^{2+} aqua ion (1.54 eV or 805 nm), whereas strong ligands (Ac^- and NO_2^-) lead to absorption at higher energies than for the pure Cu^{2+} aqua ion.

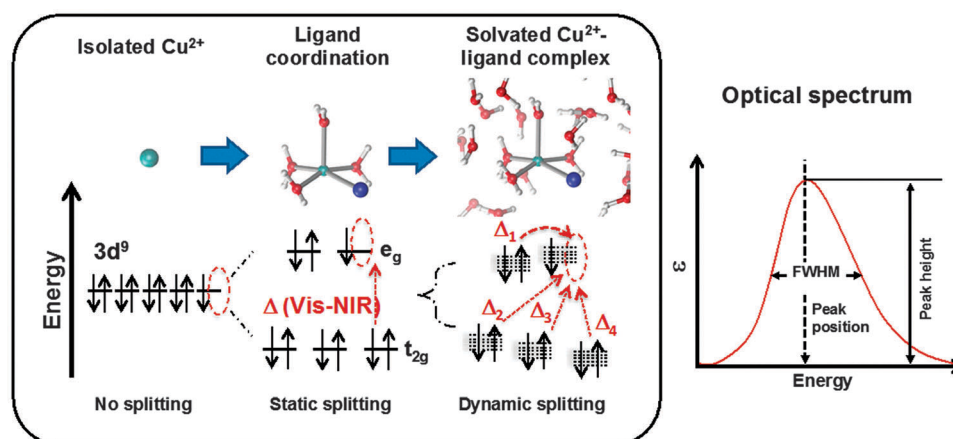


Fig. 1 Schematic of dominant sources of fine splitting in the energies of Cu^{2+} d orbitals that contribute to the optical absorption spectrum of solvated Cu^{2+} –ligand complexes. The symbol Δ represents the energy split between the e_g and t_{2g} states in the conventional crystal field description; symbols Δ_1 to Δ_4 display the fine splitting of the d levels due to additional environmental perturbations. The resulting optical spectrum is shown schematically in the right-hand panel, with its profile defined by the peak position, peak height, and full width half maximum (FWHM).

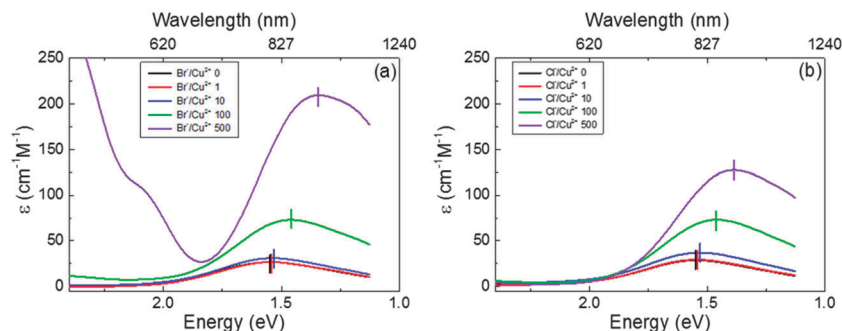


Fig. 2 Optical absorption spectra of 0.01 M Cu^{2+} with different weak ligand-to- Cu^{2+} concentration ratios in the Vis-NIR range; (a) Br^- and (b) Cl^- . The vertical line segments indicate peak position at maximum absorption for each ligand concentration.

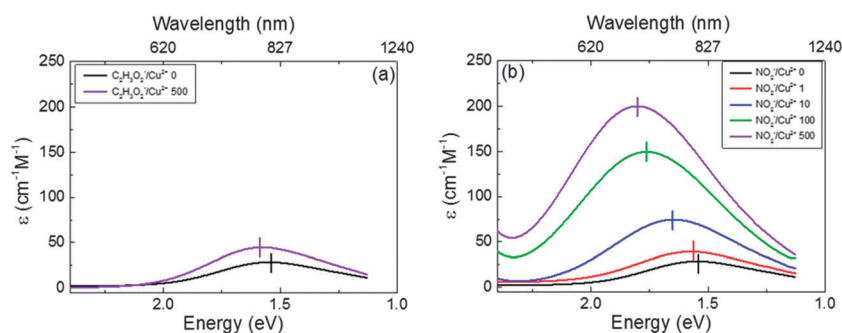


Fig. 3 Optical absorption spectra of 0.01 M Cu^{2+} with different strong ligand-to- Cu^{2+} concentration ratios in the Vis-NIR range; (a) Ac^- and (b) NO_2^- . The vertical line segments indicate peak position at maximum absorption for each ligand concentration.

In addition, the shifts are greatest for Br^- and NO_2^- , the weakest and strongest of the tested ligands, respectively. This is as expected based on the respective ligand-field strengths of the complex ligands.² In addition, the shift in the absorption peak energy is additive with ligand concentration, as has been discussed at length by previous authors.^{5–7} However, there are other additional effects that are not directly attributable to ligand field theory. For instance, ligand substitution leads to significant increases in the absorption amplitude, for both strong and weak ligands. Moreover, there is a strong concentration effect on the absorption amplitude; *e.g.*, as ligand concentration is increased, there is a more significant increase in the amplitude. Similar observations have been reported by Friedman *et al.* for Cu^{2+} complexes in acetone–water mixtures where the extinction coefficient increased as H_2O was replaced by acetone in the solution.²⁰ The absorption peaks also deviate from a purely Gaussian distribution by skewing their centers towards higher energies.

To better understand the origins of the experimental spectral profiles in Fig. 2 and 3 and to define trends in the optical absorption behavior of the ligand complexes, certain key parameters of the experimental spectral profile for each ligand and concentration are plotted in Fig. 4. In particular, the peak position of the absorption profile in the 1.0–2.3 eV range representing the energy where the maximum molar extinction coefficient is observed (see Fig. 1), the peak height representing the maximum value of the molar extinction coefficient, the estimated full width half maximum (FWHM) of the spectral

profile and the integrated oscillator strength are extracted. For the Cu^{2+} aqua complex and all ligands at all tested concentrations, a clear relationship emerges between the peak position and its height (Fig. 4a). The molar extinction coefficient is lowest for the aqua complex, and increases almost linearly with the shift in peak position regardless of the shift direction. Here, it should be noted that the peak position includes cumulative effects from both the individual ligand field strength and the concentration-dependent level of ligand substitution (these two effects will be discussed separately later). On the other hand, the peak width (FWHM) in Fig. 4b changes very little with ligand strength or level of substitution (standard deviation of ~ 0.04 eV, compared to an average FWHM of ~ 0.66 eV). Because the FWHM is relatively constant, the oscillator strength in Fig. 4c (determined by a Gaussian fit to the integrated area under the peak) mirrors the dependence of the peak height in Fig. 4a.

The salient trends in the experimentally measured peak position, width, and oscillator strength displayed in Fig. 4 merit a broader question as to what additional geometric, chemical, and electronic structural information lies hidden in the spectra of the ligand complexes. In addition to providing fundamental understanding, such information is crucial for guiding the proper interpretation of optical spectra and for constructing proper theoretical models that more closely mimic experimental conditions. Accordingly, the results in Fig. 2–4 are accompanied by a detailed first-principles approach based on different computational “schemes” that are introduced to probe potential

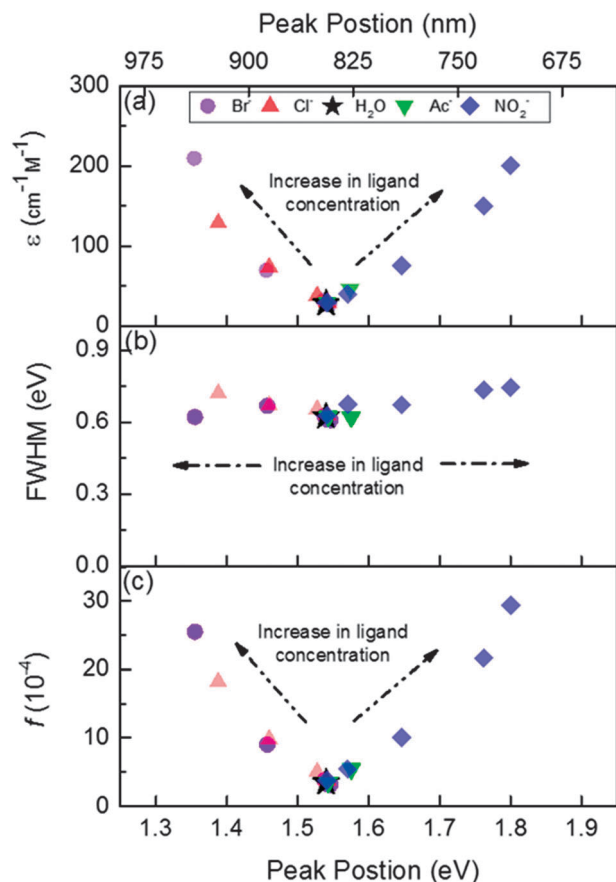


Fig. 4 Experimental correlation between the measured peak position of the Cu^{2+} absorption spectrum in the Vis-NIR range for all tested Cu^{2+} –ligand complexes and: (a) the absorption peak height, (b) the FWHM of the absorption spectrum and (c) the oscillator strength f estimated from (a) and (b). The arrows indicate trends with increased ligand concentration.

contributors to the peak profile individually rather than collectively. By comparing the computational predictions to trends in the actual spectra, the dominant factors controlling each peak feature in Fig. 4 can be assessed. The focus is on explaining the behavior of four features: the peak position, oscillator strength, width, and skew, as well as the observed relationships between them.

In addition, four different individual “ingredients” were identified as potentially relevant for determining the spectral profile for a given ligand type and overall concentration. These four ingredients include: (1) the static distortion of the electronic orbitals due to the chemical identity of the ligands (*i.e.*, fine structure due to d-level splitting); (2) the effect of the specific water and ligand coordination around the central Cu^{2+} ion; (3) the degree of dynamical geometric distortion within the complexes due to thermal and solvent perturbations; and (4) ensemble averaging of different possible individual levels of ligand substitution that may coexist at a given overall ligand concentration. In order to explore these individual ingredients, theoretical schemes were devised that combine TDDFT computations of transition energies and oscillator strengths with static and FPMD-based descriptions of solvated coordination complexes to successively introduce each into an increasingly

realistic simulation framework. These schemes allow us to carry out controlled computational “experiments” probing relative contributions of different physical factors in a way that is inaccessible to spectroscopic measurements. The four schemes are introduced briefly below, ordered from simplest to most complex; further details can be found in the Methods section.

I. Chemical identity (CI) scheme

For the CI scheme, a five-fold coordinated aqua complex in an octahedral symmetry (*i.e.*, pyramidal) was constructed, based on previous results^{13,21–25} showing strong evidence from first-principles dynamics simulations and X-ray spectroscopy that this is the most common configuration for Cu^{2+} in solution. Ligands were substituted for water molecules in the equatorial plane, and the geometry of each resulting complex was allowed to relax fully before computing the transition energies and oscillator strengths. The CI scheme assumes five-fold coordination is always retained upon ligand substitution, and no explicit thermal/solvent broadening effects are included.

II. Water coordination (WC) scheme

For the WC scheme, transition energies and oscillator strengths were computed for geometrically relaxed complexes with different coordination numbers n ($n = 3, 4, 5, 6$) at each level of ligand substitution. The spectral properties of these complexes were then weighted statistically based on the frequency of the coordination environments observed within a full FPMD simulation of the solvated complexes (in several instances, the five-fold coordination assumed in the CI scheme is not preferred; see Table S1, ESI†). The WC scheme goes beyond the CI scheme to account for variability in the coordination number, which has been shown to be relevant for Cu^{2+} in solution,^{13,23} but includes no explicit solvent/thermal broadening.

III. Geometric distortion (GD) scheme

For the GD scheme, transition energies and oscillator strengths were computed based on many FPMD frames at fixed ligand substitution, considering the full geometry of all molecules within the first solvation shell of the central copper atom. The GD scheme explicitly includes solvent/thermal broadening effects in addition to the dynamical variability in ligand coordination afforded by the WC scheme, and is similar to the methodology used by other groups to investigate the spectra of ions in solution.^{12,13} However, it neglects the possibility of different levels of ligand substitution that may coexist in the solution at a given ligand concentration.

IV. Ensemble average (EA) scheme

For the EA scheme, the transition energies and oscillator strengths for each level of ligand substitution from the GD scheme are ensemble averaged according to the relative probability of finding each at the experimental ligand concentrations. The probabilities are computed from stability constants derived from the spectroscopic studies of ref. 17, 26 and 27. This scheme is a generalization of the GD scheme, and contains the most complete physics among the four.

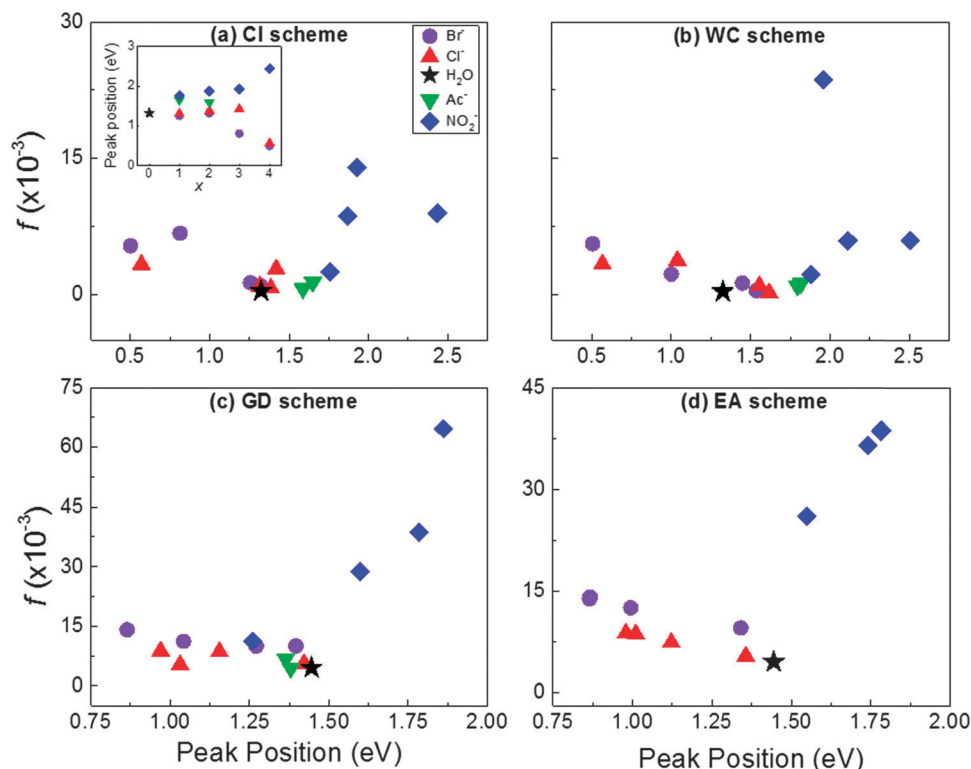


Fig. 5 Oscillator strength versus peak position for all tested complexes, calculated within each of the four schemes described within the text: (a) CI, (b) WC, (c) GD, and (d) EA (note the differences in scale). The inset in (a) shows the dependence of peak position on ligand substitution x for the CI scheme.

The key spectral features predicted by each scheme are shown in Fig. 5. Within the simplest CI scheme (Fig. 5a), which already contains the most basic elements of ligand-field theory, the ordering of the peak position for the four ligands matches the spectrochemical series as expected. In addition, although higher levels of ligand substitution do not always give rise to stronger shifts in the peak energy in the CI scheme (e.g., Ac^- , single- vs. double-substituted Br^- , and the Cl^- series), the qualitative relationship between the level of ligand substitution x and the peak position for each of the four schemes is already evident (see inset of Fig. 5a, as well as Fig. S2, ESI†). Using more accurate schemes (e.g., GD, EA) systematically improves the predicted magnitudes of the spectral shift and refines the relationship between x and the peak position (Fig. S2, ESI†). The inclusion of solvent/thermal effects in the GD scheme (Fig. 5c and Fig. S2, ESI†) significantly reduces the ligand-induced peak shift. By comparison, including configurational (WC) or ensemble averaging (EA) of different n and x has a much smaller impact.

The CI scheme largely predicts the peak position (Fig. 5a), suggesting this position is predominantly determined by the chemical identity of the ligand in accordance with ligand field theory. This effect is further visible in Fig. 6, which plots the charge density associated with each of the singly substituted CI complexes. The stronger ligands (Ac^- and NO_2^-), which can be thought of as possessing greater covalence, tend to show more density overlap and distortion of the Cu^{2+} density. By contrast, the weakest ligand, Br^- , shows the least density overlap and Cu^{2+} density distortion. Moreover, the LUMO orbitals of the

minority spin channel for each of the singly substituted complexes, also shown in Fig. 6, exhibit characteristics compatible with empty $d_{x^2-y^2}$ orbitals as expected from ligand field theory. More accurately accounting for the correct water coordination in the WC scheme (which on average is lower than the five-fold coordination assumed by the CI scheme; see Table S1, ESI†) tends to slightly blueshift the peaks at lower substitution levels. This is most likely a manifestation of the effect discussed by Prenesti *et al.*, in which spectral redshifts were associated with the presence of axial ligands.^{14,28}

Nevertheless, the relationship between the oscillator strength and the peak position is not captured until solvent/thermal effects are taken into account in the GD scheme (Fig. 5c). This is because the description of the oscillator strength in the CI and WC schemes is qualitatively incomplete, and fails to exhibit the expected dependence on x (Fig. S3, ESI†). The GD scheme (Fig. 5c) substantially improves the description, especially for high ligand concentrations. The EA scheme (Fig. 5d) reproduces the full qualitative dependence, particularly by completing the picture for the weaker ligands. The computed values of the oscillator strength depend very strongly on the calculation scheme, and are mainly enhanced once environmental (solvent/thermal) factors are included.

The peak width is derived from the spectral broadening, which has two primary origins: static broadening, due to the spread in the electronic levels; and dynamic broadening, due to thermal and solvent effects (see schematic in Fig. 1). These two factors are explored in Fig. 7, based on the GD scheme that is

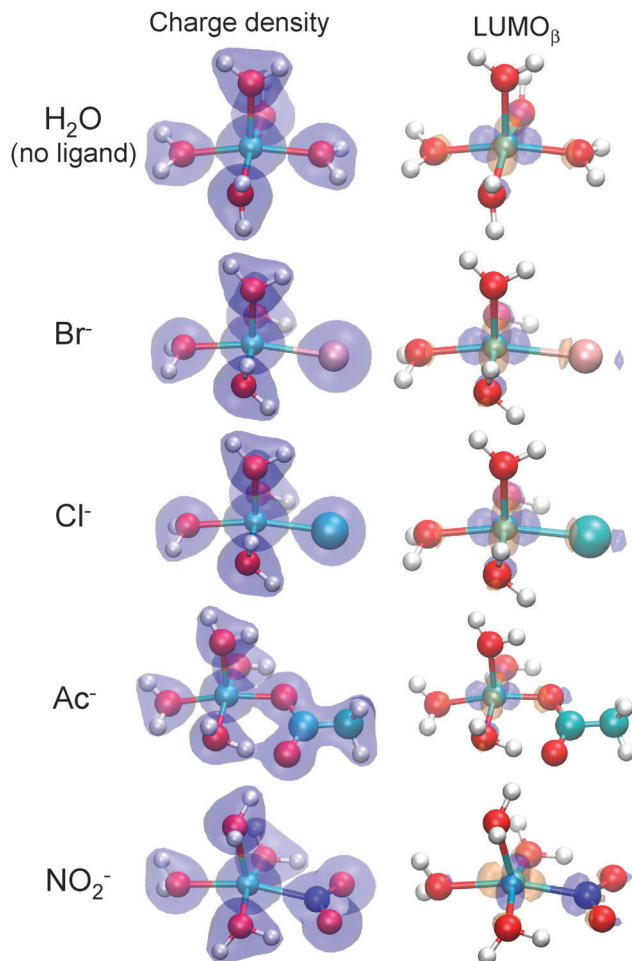


Fig. 6 Isosurfaces of the charge density (left) and LUMO orbital of the minority spin channel (right) for single-ligand substitution of the tested Cu–ligand complexes, computed within the CI scheme. Isosurfaces represent $\pm 0.08e$ (blue/orange). The substituted ligand is oriented at the right side of each figure.

the first to include both static and dynamic broadening explicitly. The horizontal axis of Fig. 7 shows the d–d transition energy associated with each of the four distinct d levels (Δ_1 through Δ_4 in Fig. 1), statistically averaged over all dynamics frames. The spread ($\Delta_4 - \Delta_1$) across the Δ_i transitions, which approximates the static electronic broadening of the peak, is reasonably consistent across all tested configurations (average = $0.52 \text{ eV} \pm 0.14 \text{ eV}$; see Table S3, ESI[†] for a breakdown by ligand type). The vertical axis of Fig. 7 shows the FWHM of the distribution Δ_i of transition energies from the configurations explored in the dynamics, with the four electronic transitions (see Fig. 1) examined individually. It provides a measure of the dynamic broadening associated with each transition. This quantity is also quite consistent for all tested configurations and transitions (average = $0.68 \pm 0.14 \text{ eV}$), and is similar in magnitude to the static contribution. Highly coordinated NO₂⁻ exhibits the most static and dynamic broadening, but the range is nevertheless comparable. The results in Fig. 7 also illustrate that Δ_i generally decreases with increasing average transition

energy; in other words, transitions that are higher in energy tend to be sharper, whereas lower-energy transitions are broader. This turns out to be related to the skew shape of the observed spectra, discussed in detail below.

Discussion

By synthesizing the simulation results in Fig. 5–7 and comparing with the experimental observations in Fig. 4, the physics underlying the peak profile can be deduced and interpreted. As noted above, the general trend of the peak position as a function of ligand identity can be readily rationalized in light of ligand field theory, consistent with the visibility of the trend even in schemes that neglect dynamical contributions. The fact that the peak position correlates directly with the level of ligand substitution in a way that is largely additive further implies that the ligand-field effect compounds local interactions between ligands and coordinating d orbitals. This is similar to conclusions reached by previous theoretical studies that considered substitution in the equatorial plane.^{5–7} The number of coordinating axial water molecules is comparatively less relevant for determining the peak position (compare Fig. 5a and b and Fig. S2a and b, ESI[†]); this reflects weaker interaction of the axial ligands with the Cu²⁺ d orbitals due to the Jahn–Teller distortion and agrees with previous investigations.^{14,28}

However, the trends in the oscillator strength, and their connection to the peak positions, depend on factors other than the field strength alone. For instance, both strong and weak ligands give similar trends in the oscillator strength (Fig. 4c). This is best understood in terms of ligand-induced symmetry breaking. As new ligands displace one or more water molecules to form a new mixed metal–ligand complex, hybridization of the Cu²⁺ d electrons will perturb the electronic orbitals and reduce the symmetry. The lowered symmetry will lead to a higher probability of d–d transition and thus the amplification of the absorption, regardless of the specific bonding mechanism. Within this logic, the oscillator strengths of both strong and weak ligands should respond similarly to distortion of the central Cu²⁺ orbital symmetry, as we observe.

According to the results of Fig. 5c and the corresponding concentration-dependent values in Fig. S3 (ESI[†]), the trend in the oscillator strength begins to be predicted only when combining the ligand-induced orbital distortion with the full space of geometric distortions due to thermal and solvent effects. Averaging over multiple coordination complexes that are simultaneously present in the solution further improves the description. It is concluded that both ligand-induced (*i.e.*, chemical) and thermal/solvent-induced (*i.e.*, mechanical/geometric) distortions in the electronic structure contribute to the molar extinction coefficient (Fig. 4a) and the oscillator strength (Fig. 4c). These two factors can be considered to have static and dynamic origins, respectively. The presence of multiple coordination complexes with different levels of substitution in each solution may also be relevant, as suggested in ref. 17–19,

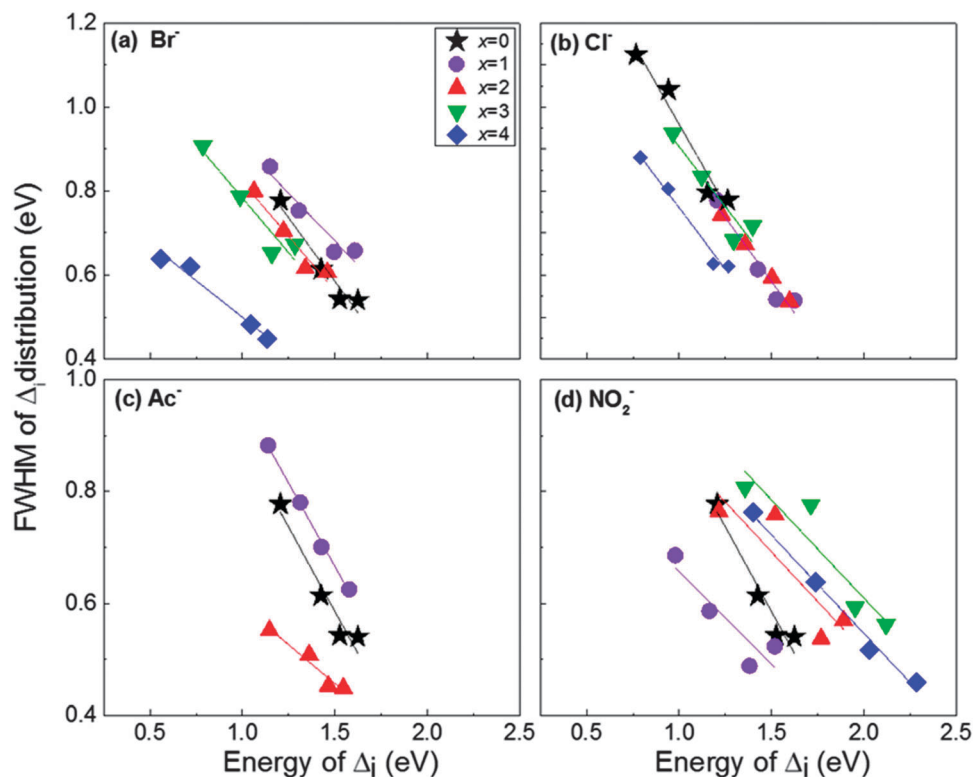


Fig. 7 FWHM of Gaussian fit to computed distributions of Δ_i , plotted against the average Δ_i transition energy from first-principles molecular dynamics frames within the GD scheme. Data represent simulations with (a) Br^- , (b) Cl^- , (c) Ac^- , and (d) NO_2^- at each level of ligand substitution x . Linear fits to each data set are shown.

although only for intermediate ligand concentrations and to a much lesser extent.

Careful examination of Fig. 5 (and Fig. S2 and S3 in the ESI†) also reveals that there is an intrinsic coupling between the static and dynamic origins discussed above. Examining the aqua complex, which includes no additional ligand-induced chemical (static) distortions, it is observed that thermal/solvent-induced (dynamic) distortions have only a minor effect on the peak energy, but a huge effect on the oscillator strength (f). This leads to the logical conclusion that f is more sensitive to thermal/solvent-induced distortions, whereas the energy is primarily predicted by chemically induced distortions. On the other hand, looking at ligand-substituted complexes, it is concluded that the sensitivity of the peak position to dynamical effects actually depends on the identity and concentration of the ligand: much larger dynamical effects on the peak position are observed for the strongest and weakest ligands, and for the highest ligand concentrations (Fig. 5c). In other words, the presence of dynamical fluctuations due to solvent/thermal effects tends to reduce the energy shift of the peak, while simultaneously increasing the oscillator strength. This can be understood in terms of the effect on the crystal field that splits the d levels according to the depiction in Fig. 1. For complexes with octahedral symmetry, the largest splitting—and hence the highest peak shifts—will occur when the Cu^{2+} d orbitals are well aligned with the ligand electrons, which will be closest to the ideal relaxed geometry where the bond angles approach 90° .

Once dynamical effects are included, deviations will necessarily lead to configurations with reduced symmetry and thus diminish the crystal field splitting,^{2,4} thereby decreasing the peak shifts as seen in Fig. 5.

Furthermore, the oscillator strength depends on the electronic distortion of the d orbitals, which can be enhanced either from chemical (*i.e.*, ligand substitution) or geometric (*i.e.*, thermal/solvent) perturbations to the symmetry. Consequently, its value tends to increase upon inclusion of dynamical effects (note that this same interpretation implies that the oscillator strength should increase with temperature, which is confirmed experimentally for the aqua complex in Fig. S4, ESI†). Comparing Fig. 5a and b with 5c and d, the highest sensitivity to thermal/solvent effects is observed for complexes with the highest degrees of ligand substitution. These observations lead to the conclusion that the static (ligand-induced) and dynamic (thermal/solvent-induced) distortions are in fact coupled. It is speculated that the chemomechanical coupling between them is ultimately responsible for the relationship between the peak position and oscillator strength in Fig. 4c.

The consistency of the spectral width across the tested complexes in Fig. 4b is also somewhat surprising. However, this can be rationalized in light of the results of Fig. 7. The simulations clearly indicate that both the electronic broadening from additional fine structure in the d orbitals (which is a static effect), and the thermal/solvent broadening (which is a dynamical effect), are largely consistent across all of our

tested complexes. Since these two factors are the dominant contributors to the overall spectral broadening behavior (quantified by the FWHM), the spectral width changes little with ligand identity or concentration.

The results of Fig. 7 also explain why the spectral profiles of the absorption band shown in Fig. 1 and 2 are not strictly Gaussian, but are skewed towards higher energies. This is because the thermal/solvent broadening is inhomogeneous, and decreases linearly with the transition energy of Δ_i . As a result, the lower-energy edge of the spectral profile is more broadened than the higher-energy spectral edge. This behavior can be related to the lower sensitivity of higher-energy transitions to local changes in geometry. In other words, within a given complex, the levels that are most perturbed electronically by the presence of the ligands are also the least sensitive to geometric factors. A demonstration of how the electronic and thermal/solvent broadening effects can combine to give rise to the experimentally observed peak shape of the aqua complex based on the four contributing transitions Δ_i is shown in Fig. S5 (ESI[†]). Significantly, the slope of the relationship between the transition energy and its thermal broadening (Fig. 7) is quite consistent for a given ligand type, regardless of the specific level of ligand substitution x . Even across the different ligand types, the variation of the slope among the ligand types is not especially large (± 0.14 , compared to an average slope of -0.48 across all complexes); nevertheless, stronger and weaker ligands tend to generate shallower slopes in Fig. 7 (computed slopes for each ligand type can be found in Table S3, ESI[†]). The universality of these relationships illustrates yet another example of implicit coupling between static (*i.e.*, electronic) and dynamic (*i.e.*, thermal/solvent) contributions to the peak shape. It should be pointed out that the calculated slope could be used to quantitatively refine future descriptions of spectral profiles associated with d–d transitions.

Methods and approaches

Preparation of Cu²⁺ aqueous solutions

Aqueous cupric salt solutions were prepared volumetrically from stock solutions made at 10 times the required molarity. Deionized water was subsequently added to produce each solution to the desired molarity. Because perchlorate ions do not complex with metal ions in aqueous solution,²⁰ copper perchlorate dehydrate salt (Alfa Aesar) was used to produce a solution of Cu²⁺ aqua complex. A concentration of 0.01 M of Cu²⁺ was used to ensure spectral measurements would neither saturate nor null the detector on the spectrometer. High purity (99.98% purity) sodium salts (Sigma Aldrich, J. T Baker, and Alfa Aesar) were used to provide each of the four different displacement ligands, namely, Br[−], Cl[−], Ac[−], and NO₂[−]. The ligand-to-Cu²⁺ concentration ratios used for Br[−], Cl[−], and NO₂[−] were 1:1, 10:1, 100:1, and 500:1. For Ac[−], only the highest concentration ratio (500:1) was tested to avoid contamination by possible side reactions between the ligand and the background ClO₄[−] ion, such as the formation of CO₂ due to redox chemistry.^{29,30}

The solution ionic strength was fixed at 5 M by mixing sodium perchlorate with sodium ligand salts of proper amount to ensure that high concentrations of copper ligand complexes were achieved.¹⁷ To avoid the formation of polynuclear complexes, the ligand concentration was chosen to be either equal to or greater than that of the Cu²⁺ ions.³¹ Sodium ions in solution do not form complexes and have no d electrons to introduce interfering spectral bands in the Vis-NIR range to the Cu²⁺ complexes. In addition, the use of sodium perchlorate ensures that the solution pH remains close to neutral, which avoids complications associated with protonation of ligands; such pH-induced protonation has been shown to alter the spectral profile of titratable ligands in Cu²⁺ complexes.¹⁵ All chemicals utilized were reagent grade and were used as received. No precipitation was observed in any of the solutions throughout the spectrometry measurements.

Optical absorption spectroscopy

The optical extinction coefficients of the Cu²⁺ salt solutions were determined from transmission measurements in the 200–1100 nm spectral range which were collected using a suitable spectrophotometer (Shimadzu model UV-1601 PC) with the solution placed in 1 cm quartz cuvettes. To minimize background and interference from water absorption in the NIR range, copper-free reference solutions were carefully prepared with identical chemical composition and ionic strength to those of the appropriate copper-containing test solutions. Transmission measurements were used to calculate the absorption coefficient of Cu²⁺ (α , cm^{−1}) at the wavelength of interest by utilizing the exponential form of Beer's law.^{32,33} The molar extinction coefficient (ϵ , cm^{−1} M^{−1}) was subsequently computed following the relationship $\alpha = \epsilon \cdot c$ where c is the Cu²⁺ concentration in solution with units of molarity (M).

Quantum chemistry simulations

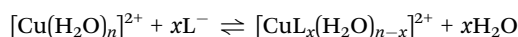
Consideration of the full solvation environment is necessary for accurately reproducing the structural properties of the solvated Cu²⁺ complexes.³⁴ Accordingly, FPMD simulations of solvated Cu²⁺–ligand complexes were performed within the Quantum-ESPRESSO package³⁵ using density functional theory (DFT) in the plane-wave pseudopotential approximation. Ultrasoft pseudopotentials³⁶ were used for all atoms (with cutoffs of 30 and 300 Ry for the plane-wave basis and charge density, respectively), based on the Perdew–Burke–Ernzerhof (PBE) exchange–correlation functional.³⁷ A time step of 8 a.u. and an effective mass of 500 a.u. were used, with hydrogen treated as deuterium to facilitate the larger time steps. The water was first equilibrated for 10 ps independently without Cu²⁺, then for another 10 ps with Cu²⁺ added before adding any other ligands. Following ligand addition, another 5 ps of equilibration was performed for each complex before acquiring 40 ps of production run trajectories. All dynamics were run in the NVT ensemble at 380 K to correct for the diffusive properties of water at ambient temperatures with the PBE functional.³⁸ Periodic supercells were cubic, and contained the Cu²⁺ ion with 48 water molecules (substituted as necessary with ligands) at the experimental density.

DFT geometry relaxations and single-point calculations of isolated Cu^{2+} complexes were performed within the NWChem software package.³⁹ TDDFT¹⁶ within the Tamm–Dancoff approximation⁴⁰ was used to obtain the optical excitation energies. Similar approaches have been shown to be successful in predicting optical spectra of other transition-metal complexes.^{12,13,41} The Baer–Neuhauser–Lifshits (BNL) range-separated hybrid functional was used,⁴² which treats short-range interactions within DFT and uses a Hartree–Fock formalism for the long-range interactions to provide the correct long-range asymptotic behavior.⁴³ This choice was motivated by a desire to describe different possible types of localized and charge-transfer excitations within the transition-metal complexes. A range separation parameter of 0.3747 was chosen by enforcing Koopmans’ Theorem to fix the ionization potential to the highest Kohn–Sham eigenvalue of the Cu–aqua complex.⁴² The COSMO model⁴⁴ was used to simulate a solvation environment for both the DFT and TDDFT calculations.⁴⁵

An augmented cc-pVTZ basis was used for Cu atom, and an augmented cc-pVDZ basis for all other atoms (in the present work, these larger basis sets were found to be required for proper convergence of the excitations).⁴⁶ To prevent improper spin state contamination in the localized basis, restricted Hartree–Fock calculations on the ligand and Cu atoms were run separately with dummy point charges substituting the absent species, then the vectors were used to run unrestricted Hartree–Fock calculations on the full system. These vectors were then used as inputs to the DFT and TDDFT calculations. As discussed below, for computing the TDDFT transitions, some geometries were based on relaxations of ideal complexes, whereas others were taken directly from the FPMD simulation trajectories. As a general rule, the TDDFT calculations tend to systematically overestimate the oscillator strengths, as well as the ligand-induced spectral shifts. This may be attributed in part to the absence of an explicit solvent in the TDDFT configurations, which will tend to strengthen the ligand-induced distortion.

Computational schemes for investigating spectral contributions

In general, ligand substitution of the aqua complex occurs according to the following chemical equation:



where L represents the substituting ligand, x is the level of substitution (number of substituted water molecules), and n is the first-shell coordination number of Cu^{2+} . Based on this formalism, four different computational schemes have been introduced in order to successively probe possible individual contributions to the observed spectrum. The procedures for computing the spectral features within each scheme are outlined in detail below.

Chemical identity (CI) scheme. For the CI scheme, ligands were substituted in the equatorial positions of a geometrically relaxed, five-fold coordinated aqua complex. The geometry of each resulting complex was then allowed to relax before

computing the relevant TDDFT transition energies and oscillator strengths. All unique stereoisomers were tested, although only the results for the most stable complexes are reported. Stereoisomers based on ligand substitution of the axial water molecule were found to be universally less stable than in-plane substitution. The reported peak positions E_{avg} are based on an average of the four TDDFT transitions E_i weighted by their respective oscillator strengths f_i : $E_{\text{avg}} = \sum_{i=1}^4 \frac{1}{4} f_i E_i$. The reported oscillator strengths f_{tot} represent the sum over the partial oscillator strengths for each of the four transitions: $f_{\text{tot}} = \sum_{i=1}^4 f_i$.

Water coordination (WC) scheme. For the WC scheme, TDDFT transition energies and oscillator strengths are first calculated for geometrically relaxed complexes with different coordination numbers n ($n = 3, 4, 5, 6$) and at each level of ligand substitution x ($x = 1, 2, 3, 4$). Note that for the Ac–ligand, $x = 3$ and $x = 4$ were found to be unstable; the same was true for all complexes with substitution levels $x > 4$. Next, for every fixed value of x , relative probabilities of n (p_n) were obtained by statistically sampling the FPMD frames of the solvated complexes. Values of p_n for each ligand and each value of x can be found in Table S1 (ESI†). The average coordination found here for the aqua complex is similar to but slightly lower than those reported by Pasquarello *et al.* and Blumberger *et al.*^{13,21} The difference reflects likely the higher simulation temperature used here. The reported peak positions E_{avg} are based on an average of the four TDDFT transitions $E_{i,n}$ for each n , weighted by their respective oscillator strengths $f_{i,n}$ and probabilities p_n : $E_{\text{avg}} = \sum_{n=3}^6 \sum_{i=1}^4 \frac{1}{4} f_{i,n} E_{i,n} p_n$. The total oscillator strength is given by $f_{\text{tot}} = \sum_{n=3}^6 \sum_{i=1}^4 f_{i,n} p_n$.

Geometric distortion (GD) scheme. For the GD scheme, 150 frames sampled every 200 fs were chosen from the production runs for each value of x . Configurations for the TDDFT calculations were extracted from the FPMD frames by considering all molecules with atoms within 3.1 Å of the central copper atom, representing the first solvation shell. The reported peak positions E_{avg} are based on a time average of the four TDDFT transitions $E_{i,t}$, each of which is weighted by the corresponding $f_{i,t}$: $E_{\text{avg}} = \frac{1}{T} \sum_{t=1}^T \sum_{i=1}^4 \frac{1}{4} f_{i,t} E_{i,t}$. Here the index t runs over the $T = 150$ frames included in the average. The total oscillator strength is given by $f_{\text{tot}} = \frac{1}{T} \sum_{t=1}^T \sum_{i=1}^4 f_{i,t}$.

Ensemble average (EA) scheme. For the EA scheme, the x -dependent values of $E_{\text{avg},x}^{\text{GD}}$ and $f_{\text{tot},x}^{\text{GD}}$ from the GD scheme are ensemble averaged according to the relative probability p_x of each x ($x = 1, 2, 3, 4$) at a given experimental ligand concentration (1:1, 10:1, 100:1, or 500:1). Accordingly, E_{avg} and f_{tot} become $E_{\text{avg}} = \frac{1}{4} \sum_{x=1}^4 p_x E_{\text{avg},x}^{\text{GD}}$ and $f_{\text{tot}} = \frac{1}{4} \sum_{x=1}^4 f_{\text{tot},x}^{\text{GD}}$. The stability constants and probabilities p_x are computed from references,^{17,26,27} following the procedure outlined in the ESI† (Fig. S1 and Table S1).

Because experimental stability constants were only available for NO_2^- , Cl^- , and Br^- , only values for these ligands within the EA scheme are reported here.

Conclusions

In conclusion, the absorption spectra obtained from four model Cu^{2+} -ligand complexes in solutions are combined with first-principles simulations to examine many of the key physical contributors to the spectral profile characteristics of the Vis-NIR absorption spectrum. Interestingly, it is observed that the peak position and oscillator strength are intrinsically coupled for all tested ligand complexes. This is attributed to a subtle yet important connection between ligand identity and the sensitivity of the spectral features to solvent and thermal distortions. The spectral width is surprisingly consistent across the tested complexes, which is a direct result of the fact that both the electronic and thermal/solvent broadening effects are independent of ligand identity and concentration. At the same time, the thermal/solvent broadening is found to depend linearly on the optical transition energy, which leads to inhomogeneous broadening behavior and has the nonobvious consequence of skewing the peak profile towards higher energies.

The presented results conclusively demonstrate that conventional interpretations based on ligand field theory alone are insufficient for capturing the full characteristics of the absorption profile. Moreover, qualitative correlations between various aspects of the profile emerge upon deeper consideration of the physiochemical origins of the spectrum. The current study suggests a compelling route for rationally designing and experimentally tuning the spectral profile of d-d transitions in metal-ligand complexes. The insights can be applied to better interpret experimental spectra, to help design materials with tailored optical properties as well as to provide a meaningful template for improving the accuracy of theoretical spectroscopic predictions.

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