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Atomic scale evidence of the switching mechanism in a photomagnetic CoFe dinuclear Prussian Blue Analogue

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Abstract

Molecular complexes based on Prussian Blue Analogues have recently attracted considerable interest for their unique bistable properties combined to ultimately reduced dimensions. Here, we investigate the first dinuclear FeCo complex exhibiting both thermal and photomagnetic bistability in solid state. Through an experimental and theoretical approach combining local techniques - X-ray Absorption Spectroscopy (XAS), X-ray Magnetic Circular Dichroism (XMCD) and Ligand Field Multiplet calculations, we were able to evidence the changes occurring at the atomic scale in the electronic and magnetic properties. The spectroscopic studies were able to fully support at the atomic level the following conclusions: *(i)* the 300 K phase and the light-induced excited state at 4 K are both built from $\text{Fe}_{\text{LS}}^{\text{III}}-\text{Co}_{\text{HS}}^{\text{II}}$ paramagnetic pairs with no apparent reorganization of the local structure, *(ii)* the 100 K phase is composed of $\text{Fe}_{\text{LS}}^{\text{II}}-\text{Co}_{\text{LS}}^{\text{III}}$ diamagnetic pairs, and *(iii)* the light-induced excited state is fully relaxed at an average temperature of ≈ 50 K. In the paramagnetic phase at 2 K, XAS and XMCD reveal that, both Fe and Co ions exhibit a rather large orbital magnetic moment ($0.65 \mu_B$ and $0.46 \mu_B$, respectively under an external magnetic induction of 6.5 T) but it was not possible to detect a magnetic interaction between spin centers above 2 K.

Introduction

$$\partial_x f(u), \quad \partial_j f^j(u), \quad u f \quad \partial_x u, \quad \partial_j u \quad q_j + q_f \quad (1)$$

With growing technological interests, smart molecular materials with reduced dimensions¹⁻⁴ are being designed, synthesized and investigated for computing applications,⁵ which include, for instance, switching devices,⁶ data storage and processing,⁷ and logic gates.⁸ In these applications, a single molecule is employed to perform numerous binary operations based on logic. Molecular complexes exhibiting externally-controlled properties are well-suited for these applications because of their flexible and versatile chemistry. The ON-OFF switching capability between two molecular states, for example, magnetic (ON or 1) and diamagnetic (OFF or 0) states is termed as bi-stability. This switching phenomenon can be used to store data as binary units “0” and “1” if the molecules possess a memory effect under external stimuli (light, temperature, magnetic field, pressure etc.). To develop such switchable molecules using state-of-the-art chemistry, careful manipulation and tailoring of the molecular properties, with control down to a single spin carrier, is a current challenge.^{4,9-11} In this regard, the versatile molecular chemistry of mixed valence cyanido-bridge Prussian Blue ($\text{Fe}^{\text{II}}-\text{CN}-\text{Fe}^{\text{III}}$) and its derivatives ($\text{A}^{\text{II/III}}-\text{CN}-\text{B}^{\text{III/II}}$, where A and B are 3d transition metal ions, noted AB in the following), referred to as Prussian Blue analogues (PBA), has been exploited to engineer bi-stable systems.¹² The first evidence of light-induced magnetism in 3-dimensional (3-D) network of FeCo PBA by Hashimoto and co-workers¹³ fuelled the quest for designing photoswitchable molecule-based magnets with novel functionalities in this family. FeCo PBA magnets are unique systems exhibiting bi-stability due to an electron transfer that transforms $\text{Fe}_{\text{LS}}^{\text{II}} (S=0)-\text{CN}-\text{Co}_{\text{LS}}^{\text{III}} (S=0)$ diamagnetic entities into $\text{Fe}_{\text{LS}}^{\text{III}} (S=1/2)-\text{CN}-\text{Co}_{\text{HS}}^{\text{II}} (S=3/2)$ paramagnetic ones (LS = low spin; HS = high spin). This metal-to-metal electron transfer via the cyanido bridge can be tuned by external parameters like light, temperature and pressure.^{11,13-18} Reducing the dimensionality of the material allows the device miniaturisation, which is the ultimate goal. The first step was

to develop molecular complexes of PBA with desired thermal and photo-induced electron transfer properties. Some attempts have been made to synthesize cyanide FeCo complexes but thermal- and/or photo-induced electron transfer properties could not be observed.^{19–21} The first evidence of thermally induced metal-to-metal electron transfer was reported in a pentanuclear cyanido-bridged $[\text{Fe}_2\text{Co}_3]$ molecule by Dunbar and co-workers in 2004.^{22,23} More recently, PBA based $[\text{Fe}_n\text{Co}_n]$ nanostructures such as 1-dimensional (1-D) networks,^{24–28} and molecular cube,²⁹ square,^{30–35} and dinuclear pair^{36,37} have also been synthesized. However, only few systems have been fully characterized by structural methods in their light-induced metastable state.^{33,38–40} Furthermore, there are not many examples where the light-induced electron transfer is observed at the atomic scale using XAS/XMCD techniques.^{41–45}

Recently, Koumoussi et al. succeeded in synthesizing the first dinuclear complex that exhibits both thermal- and photo-magnetic bistabilities in solid state.³⁷ This dinuclear complex is assembled from $[\text{TpFe}(\text{CN})_3]^-$ and $[\text{Co}(\text{PY5Me}_2)]^{2+}$ building blocks (Tp=hydridotris(pyrazol-1-yl)borate; PY5Me₂=2,6-bis(1,1-bis(2-pyridyl)ethyl)pyridine) and it can be seen as the elementary motif of the FeCo PBA (see Figure 1). At room temperature, the FeCo dinuclear complex in its desolvated form is in its $\text{Fe}_{\text{LS}}^{\text{III}} (S=1/2) - \text{CN} - \text{Co}_{\text{HS}}^{\text{II}} (S=3/2)$ paramagnetic state and it undergoes a transition around 167 K toward the $\text{Fe}_{\text{LS}}^{\text{II}} (S=0) - \text{CN} - \text{Co}_{\text{LS}}^{\text{III}} (S=0)$ diamagnetic state. At low temperature (below 10 K) and under white light irradiation, the diamagnetic pairs undergo a light-induced conversion toward the $\text{Fe}_{\text{LS}}^{\text{III}} (S=1/2) - \text{CN} - \text{Co}_{\text{HS}}^{\text{II}} (S=3/2)$ paramagnetic state. A characteristic increase of χT product (χ being the magnetic susceptibility) under light irradiation is observed and within 4 hours of irradiation a maximum value of $2.8 \text{ cm}^3 \text{ K mol}^{-1}$ is reached as expected for the paramagnetic FeCo pair. The electron transfer process is complete and reversible and for the first time this was observed in a dinuclear system.^{12,37} All the above mentioned changes of the electronic configurations driven by electron transfer have been proposed to explain the variation of the magnetic susceptibility measured by conventional magnetometry.³⁷ However, there has been so far no direct confirmation at the atomic level that such an electron transfer between Co

and Fe sites does indeed take place. Therefore, we have investigated the modifications of the electronic and magnetic structures in temperature and under light irradiation using X-ray Absorption Spectroscopy (XAS) and X-ray Magnetic Circular Dichroism (XMCD), which are element-specific, synchrotron based techniques. The goal of this spectroscopic study is to determine the properties of the Fe and Co ions in the three phases involved in the photo-magnetic mechanism: the 300 K paramagnetic phase, the 100 K diamagnetic phase and the 4 K photo-induced paramagnetic phase. The analysis of the XAS and XMCD experimental data is supported by Ligand Field Multiplet (LFM) calculations⁴⁶ developed by Theo Thole and magneto-optical sum rules^{47,48} in order to determine the orbit and spin magnetic moments of Fe and Co in the 4 K photo-induced paramagnetic phase. The nature of the magnetic coupling between Fe and Co ions in the dinuclear complex was also investigated using element specific magnetization curves measured by XMCD.

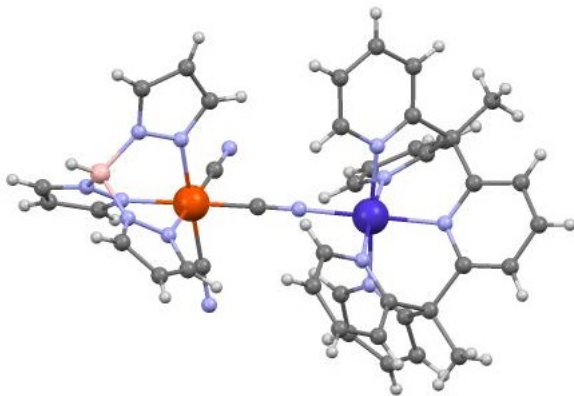


Figure 1: Molecular structure of the cationic complex of dinuclear FeCo PBA, $[(\text{Tp})\text{Fe}(\text{CN})_3 \text{Co}-(\text{PY5Me}_2)]^+$ where Tp= hydridotris(pyrazol-1-yl)borate and PY5Me₂=2,6-bis(1,1-bis(2-pyridyl)ethyl)pyridine. All anions, lattice solvents, and hydrogen atoms are omitted for clarity. Fe, Co, N, C, and B atoms are indicated in orange, dark blue, light blue, gray, and pink, respectively.

Previously, element specific and surface sensitive XAS has been successfully employed to understand bistability in other molecular systems such as spin crossover (SCO) systems,⁴⁹⁻⁵¹ or cobalt-dioxolene valence tautomers.^{41,42,52,53} In SCO compounds, one follows a high spin (HS) to low spin (LS) conversion centred on the same metallic ion while in cobalt-dioxolene

valence tautomers, an electron transfer takes place between a cobalt ion and the dioxolene ligand accompanied by a high spin to low spin conversion of the Co center. In PBAs and molecular analogs, a metal-to-metal electron transfer via cyanido ligands is accompanied also by a high spin to low spin conversion of the Co ions.^{12,43,54–59} Investigation of thermal- and photo-induced electron transfer by XAS has been reported by Sekine *et al.* on discrete systems of FeCo PBA.^{43,59} The originality of the present results stems from the recording of XAS and XMCD spectra for both metallic ions involved in the electron transfer on the same sample, thus providing a direct, atomic scale picture of the switching mechanism and possible information on the nature of the magnetic coupling between metal centers in the light-induced metastable phase.

Experimental Section

Sample Preparation

The desolvated FeCo dinuclear complex with formula $[(\text{Tp})\text{Fe}^{\text{III}}(\text{CN})_3\text{Co}^{\text{II}}(\text{PY5Me}_2)](\text{OTf})$ (referred to as compound **1**, (OTf: CF_3SO_3 , Trifluoromethanesulfonate) and the corresponding Fe and Co precursors were synthesized following the procedure reported by Koumoussi *et al.*³⁷ The chemical formulae for Fe and Co precursors are $(\text{NBu}_4)[(\text{Tp})\text{Fe}^{\text{III}}(\text{CN})_3]$, labeled compound **2** and $[(\text{Tp})\text{Co}^{\text{II}}(\text{PY5Me}_2)\text{H}_2\text{O}](\text{BF}_4)_2$, labeled compound **3**, respectively. For **1**, the metal-to-metal electron transfer in solid state was previously studied using standard magnetometric techniques, single crystal diffraction and optical reflectivity methods (see reference by Koumoussi *et al.*³⁷ and Supporting Information).

XAS and XMCD measurements

Powder sample of **1** was deposited on a double-sided conductive carbon tape suitable for cryogenic temperatures and mounted on a copper sample holder. XAS and XMCD measurements were performed at both $L_{2,3}$ and K edges of Fe and Co ions. Spectra at the $L_{2,3}$ edges

were recorded on two soft X-ray beamlines, the DEIMOS (SOLEIL synchrotron, France)⁶⁰ and the SIM (SLS synchrotron in Switzerland) beamlines.^{61,62} All spectra at $L_{2,3}$ edges were measured by recording the total electron yield (TEY) under ultra-high vacuum conditions. K edge XAS spectra were recorded at ID12 beamline^{63,64} (ESRF synchrotron, France) by measuring the total fluorescence yield.

The DEIMOS beamline is equipped with a 7 T cryo-magnet that has a variable temperature insert. To avoid any spurious signals, XMCD signal was measured by taking the difference of two XAS spectra recorded for left and right polarized X-rays with the propagation vector parallel or antiparallel to the direction of external magnetic induction \mathbf{B} . By definition, the XMCD signal is obtained by $\sigma_{\text{XMCD}} = \sigma^- - \sigma^+$ where $\sigma^- = [\sigma_L(B^-) + \sigma_R(B^+)]/2$ and $\sigma^+ = [\sigma_L(B^+) + \sigma_R(B^-)]/2$.⁶⁵ XAS and XMCD spectra for **1** were first recorded at 300, 100 and 4 K to check for thermal-induced conversion. At 4 K, the sample was irradiated with a LED ($\lambda = 660$ nm and $P = 19$ mW/cm²) for 2 hours and the photo-converted state was recorded. We also followed the relaxation of the light-induced excited state when the temperature was raised up to 50 K. The reversibility of the thermal- and photo-induced conversion has been carefully checked by recording XAS spectra for temperatures between 100 and 300 K.

To check for the nature of the magnetic coupling between the Fe and Co ions in the photo-induced state, XMCD signals should be measured in sub-kelvin temperature because the Fe–Co exchange coupling is expected to be small. On the SIM beamline, the French TBT-mK cryomagnet is a unique tool to perform XMCD measurements in the sub-kelvin range down to 300 mK.⁶¹ However, due to technical issues, the measurements could only be performed at 2 K. At 2 K, the sample was irradiated using a 660-nm LED ($P = 19$ mW/cm²) and the XMCD signal of the photo-excited paramagnetic state was measured. Thanks to XMCD, it is possible to record magnetization curves that are specific of the absorbing ion by setting the energy of the monochromator at the maximum (in absolute value) of the XMCD signal and then sweeping the intensity of the magnetic induction. As can be deduced from

the magneto-optical sum rules, the variation of the XMCD intensity at the $L_{2,3}$ edges is a measure of the magnetization of the absorbing atom.

At ID12 beamline, Fe and Co K edge XAS spectra were measured at 300 and 2 K. At 2 K, compound **1** was irradiated for 3 hours by the white light delivered by a tungsten halogen lamp ($P = 0.5 \text{ mW/cm}^2$) and then Fe and Co K edge spectra were measured in the photoexcited state.

Ligand Field Multiplet calculations

Quantitative information from the XAS and XMCD spectra can be extracted by using Ligand Field Multiplet (LFM) calculations.^{46,66,67} These calculations are performed employing the theory which has been developed by Theo Thole,⁴⁶ based on an atomic theory by Cowan⁶⁸ and for which the crystal field interactions (*i.e.*, symmetry) are described following Butler's work.⁶⁹ We have performed LFM calculations to simulate the Co and Fe $L_{2,3}$ edges spectra in octahedral or distorted environments. The parameters of the calculations are reported in Table S1 (Supporting Information). The core-hole lifetime is mimicked by a Lorentzian broadening for which the HWHM is 0.25 eV at the L_3 edge and 0.50 eV at the L_2 edge. The instrumental Gaussian broadening is $\sigma = 0.1$ eV. The definition of Dq , $D\sigma$ and $D\tau$ parameters can be found in the paper by Juhin *et al.*⁷⁰ Configuration Interaction has been used for the calculation of the Fe and Co $L_{2,3}$ edges. The definitions for the associated parameters are best found in de Groot and Kotani's book with precisions on the phase convention for V_{eg} and V_{t2g} .⁶⁷ For the calculations, the magnetic field is applied along the direction of the photon \mathbf{k} vector. The XAS and XMCD signals for powders are obtained by averaging the direction of the \mathbf{k} vector over the unit sphere with respect to the crystal field axes.

The analysis of the LFM calculations yields the spin and orbital magnetic moments for both Co and Fe ions.

Results

Thermally- and light-induced metal-to-metal electron transfer

Figure 2 shows the XAS experimental spectra at the Fe and Co L_3 edges for **1** at 300 and 100 K before LED irradiation and at 4 K after LED irradiation ($\lambda = 660$ nm). At 300 K, the spectral shape is characteristic of $\text{Fe}_{\text{LS}}^{\text{III}}$ and $\text{Co}_{\text{HS}}^{\text{II}}$ metal ions.⁷¹⁻⁷³ Peak **a** on the Fe L_3 XAS spectrum is the electronic signature of $\text{Fe}_{\text{LS}}^{\text{III}}$ ions surrounded by cyanido ligands, and peaks **a'** to **d'** on the Co L_3 XAS spectrum are mainly the contribution from $\text{Co}_{\text{HS}}^{\text{II}}$.⁷¹ When **1** is cooled down to 100 K, peak **b** at the Fe L_3 edge and peak **e'** at the Co L_3 edge become the main features. Both **b** and **e'** peaks can be respectively associated with $\text{Fe}_{\text{LS}}^{\text{II}}$ and $\text{Co}_{\text{LS}}^{\text{III}}$ metal ions, thus confirming the temperature-induced switching mechanism proposed from conventional magnetic susceptibility measurements.³⁷ Nevertheless at 100 K, **a**, **a'**, **b'** and **c'** peaks have not completely disappeared, which implies that the electronic conversion is not complete for both Fe and Co ions. One can estimate that around 25 % of the high temperature phase is still present at 100 K. This percentage is determined by linear combinations of LFM reference spectra calculated for $\text{Co}_{\text{HS}}^{\text{II}}$, $\text{Co}_{\text{LS}}^{\text{III}}$, $\text{Fe}_{\text{LS}}^{\text{II}}$ and $\text{Fe}_{\text{LS}}^{\text{III}}$ metal ions.⁵⁵ Then, **1** is further cooled down to 4 K and irradiated at 660 nm. From a straightforward comparison with the XAS signature at 300 K and with experimental and theoretical results from literature,^{44,55,57,71,72,74} it is clear that the light-induced state is built from paramagnetic $\text{Fe}_{\text{LS}}^{\text{III}}$ and $\text{Co}_{\text{HS}}^{\text{II}}$ species. The respective contributions of low spin and high spin characteristic features in the Fe and Co L_3 XAS spectra therefore clearly confirm the existence of thermal- and photo-induced electron transfers.

Thermal Relaxation of the photoinduced excited state

We have recorded the relaxation of the photoexcited state toward the thermodynamically stable diamagnetic state when the temperature is increased. Compound **1** was first cooled down to 4 K and irradiated at 660 nm ($P = 19$ mW/cm²). Then the temperature was raised

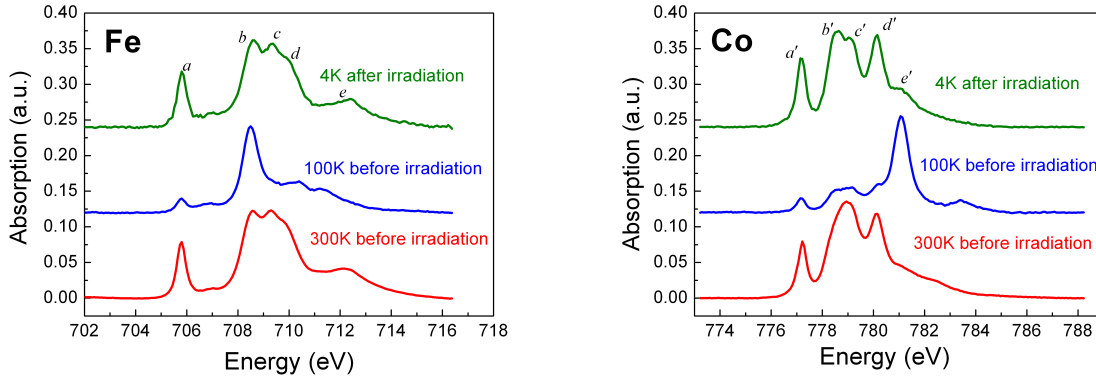


Figure 2: Experimental XAS spectra at the Fe (left) and Co (right) L_3 edge before LED irradiation at 300 K (red line), 100 K (blue line) and 4 K after irradiation (green line) ($\lambda = 660$ nm, $P = 19$ mW/cm², 2 hours) at $\mathbf{B} = 2$ T.

from 4 to 10 K and then from 10 to 50 K in steps of 5 K (the temperature rate is less than 0.1 K/mn) and at each temperature point, Fe and Co L_3 edges spectra have been recorded (Figure 3). When the temperature increases, one observes a gradual decrease of the main signature of $\text{Fe}_{\text{LS}}^{\text{III}}$ (peak **a**) and $\text{Co}_{\text{HS}}^{\text{II}}$ (peak **a'**) metal ions. As mentioned before, at 100 K the signals for Fe and Co before and after irradiation/thermal relaxation are composed of ≈ 75 % of $\text{Fe}_{\text{LS}}^{\text{II}}-\text{Co}_{\text{LS}}^{\text{III}}$ diamagnetic pairs and 25 % of residual $\text{Fe}_{\text{LS}}^{\text{III}}-\text{Co}_{\text{HS}}^{\text{II}}$ paramagnetic pairs. At a given temperature, each spectrum is analyzed as a linear combination of the spectra measured at $T = 4$ K and $T = 100$ K (Figure S1 in Supporting Information reports in more details on the fitting procedure), and this method allows the determination of the fraction of each metal ion as a function of temperature (Figure 4). One can observe that the relaxation curves for Fe and Co are almost identical indicating that the reduction of Fe ions is accompanied by the oxidation of Co ions, as expected for the electron transfer mechanism. The relaxation is almost complete at 50 K. In Figure 4, the size of the symbols is a rough estimate of the errors on the x -axis (≤ 5 K) and on the y -axis (≈ 5 %) that arise respectively from the temperature stabilization of the cold finger and from the dynamic relaxation during the recording process.

A similar series of measurements were performed between 100 and 300 K for interme-

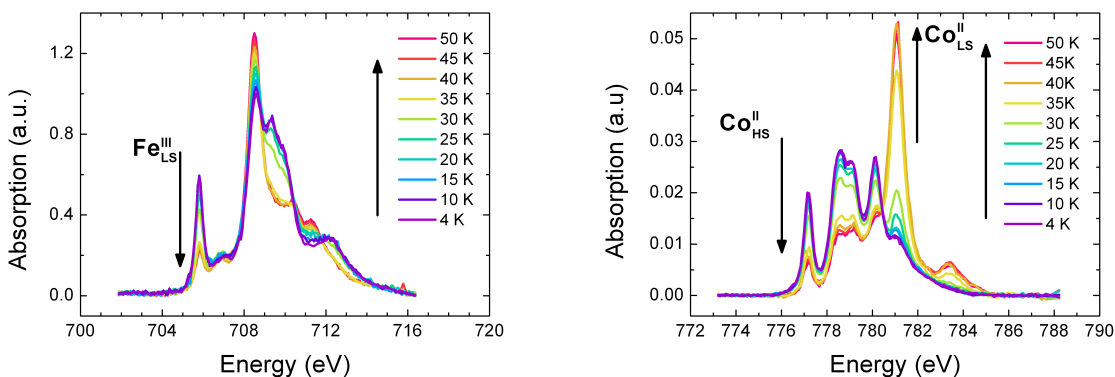


Figure 3: L_3 edge XAS spectra measured in compound **1** for Fe (left) and Co (right), following the relaxation of the light-induced $\text{Fe}_{\text{LS}}^{\text{III}}-\text{Co}_{\text{HS}}^{\text{II}}$ excited state as a function of temperature at *ca.* 0.1 K/mn, under $\mathbf{B} = 2$ T.

diate temperatures equal to 160, 165, 170, and 180 K. The percentage of each species was determined from the linear combination of the reference spectra measured at 100 and 300 K (Figure 4).

For comparison the experimental variation of the magnetic susceptibility (shown as χT) measured by conventional magnetometry is shown in Figure 4. The χT product for a paramagnetic species is independent of temperature in the case of a Curie behavior: it is zero for a diamagnetic pair and equals *ca.* $3 \text{ cm}^3 \cdot \text{K} \cdot \text{mol}^{-1}$ for the $\text{Fe}_{\text{LS}}^{\text{III}}-\text{Co}_{\text{HS}}^{\text{II}}$ paramagnetic pair. The agreement between XAS and magnetic measurements is quite good and both techniques observe the complete relaxation of the photo-induced state around 48 K and the thermally-induced conversion around 165 K (see Figure S2 for complementary information).

Reversibility of the electron transfer process

One major point was to check whether the spectral modifications observed with temperature and light irradiation were fully reversible, in order to discard any degradation of the sample that could explain these changes. Starting from the light-induced state at 4 K, we have warmed up **1** and recorded XAS spectra at 100 and 300 K. By doing so, **1** has followed a complete temperature cycle: 300, 100, 4 K and irradiation at 660 nm, 100 K, and

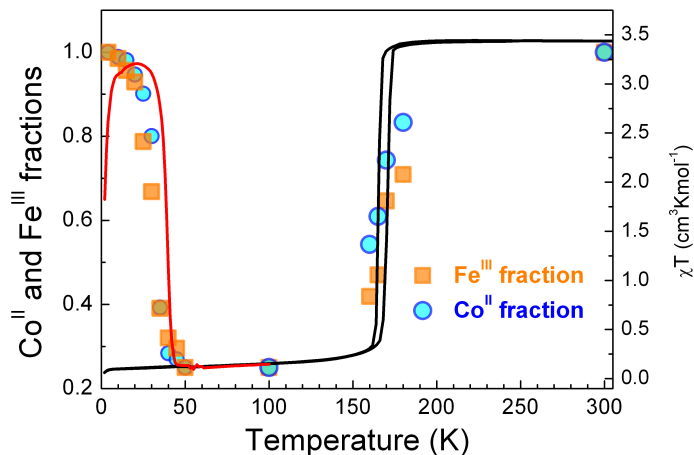


Figure 4: Fraction of the paramagnetic Co(II) and Fe(III) metals ions as a function of temperature, extracted from the quantitative analysis of XAS spectra measured at Fe and Co L_3 edge (0.1 K/min). The size of the symbols accounts for the error bars on the x and y axes. For comparison, the χT product vs T is plotted. χT is obtained from conventional magnetization measurements (0.4 K/min), in the dark (black solid line) and in the dark after white light excitation ($P = 3 \text{ mW/cm}^2$) at 10 K (red solid line).

eventually 300 K. Spectra recorded at 100 K before and after the 10 K photomagnetic conversion/thermal relaxation are almost identical at both the Fe and Co L_3 edges (Supporting Information: Figure S3). They bear the signature of $\text{Fe}_{\text{LS}}^{\text{II}}$ and $\text{Co}_{\text{LS}}^{\text{III}}$ ions with small contributions from $\text{Fe}_{\text{LS}}^{\text{III}}$ and $\text{Co}_{\text{HS}}^{\text{II}}$ ions. At 300 K, the two spectra recorded at the beginning and at the very end of the temperature cycle exhibit the clear signature of $\text{Fe}_{\text{LS}}^{\text{III}}$ and $\text{Co}_{\text{HS}}^{\text{II}}$ metal ions (Figure S4). This confirms unambiguously the complete reversibility of the electron transfer process for both the temperature-induced and the light-induced conversions. In other words, there is no sign of any sample degradation under X-ray or 660-nm irradiations.

For completeness, the Fe and Co K edges XAS spectra were recorded for **1** at 300, and at 4 K before and after light irradiation. Since the escape depth for hard X-ray photons at the Fe and Co K edges is larger than $10 \mu\text{m}$, the obtained information relates to the bulk of the sample. On the contrary when the Fe and Co $L_{2,3}$ edges are measured in TEY, the escape depth of the electrons is not larger than 5 nm so that the probed sample is essentially the very surface of the sample. The whole set of results for K edges is presented in Supporting

Information (Figures S5, S6, S7, and S8) and the conclusions are very similar to the ones obtained at the Fe and Co $L_{2,3}$ edges.

From the comparison with experimental spectra⁵⁴ or theoretical ones,^{41,75} we have been able to characterize the different electronic states (high temperature, low temperature and after light irradiation) of **1** for both Co and Fe ions. We have confirmed with soft and hard X-rays that the thermally-induced and the light-induced metal-to-metal electron transfer is accompanied by an electronic reorganization at the Co site from a LS configuration for Co(III) to a HS configuration for Co(II).

Magnetic properties of the light-induced excited state

XMCD spectra have been recorded at the Fe and Co $L_{2,3}$ edges at 2 K after photoexcitation, in an external magnetic induction of 6.5 T (Figure 5). For normalization, the background was subtracted from the XAS spectra using two arctangent functions that model the $2p_{3/2} \rightarrow$ continuum and $2p_{1/2} \rightarrow$ continuum transitions.⁷⁶ Then the maximum of the L_3 edge is set to 1 and the XMCD signal is normalized in proportion. The large intensity of the Fe L_2 edge on the XAS signal is a clear indication that the Fe ion is in a low spin state,^{77,78} while the relatively small Co L_2 edge is a sign that Co ions are in their high spin state. XMCD signals at the Fe L_3 and the Co L_3 edges are both negative, which evidences that Fe and Co total magnetic moments point in the same direction at $T = 2$ K and $\mathbf{B} = 6.5$ T. In such conditions, there is no indication of an antiferromagnetic coupling between Fe and Co magnetic moments.

The XMCD signal at the Fe $L_{2,3}$ edges has three main negative features α , γ , ζ and two moderate positive ones, β and δ . Its intensity is not small since the γ feature amounts to 57 % of the maximum of the L_3 edge. Thus, from the shape and intensity of XMCD, one expects a rather large orbital magnetic moment that is likely to overcome the spin magnetic moment. The spin sum rule is known to be non valid for the $L_{2,3}$ edges of $\text{Fe}_{\text{LS}}^{\text{III}}$ so that the

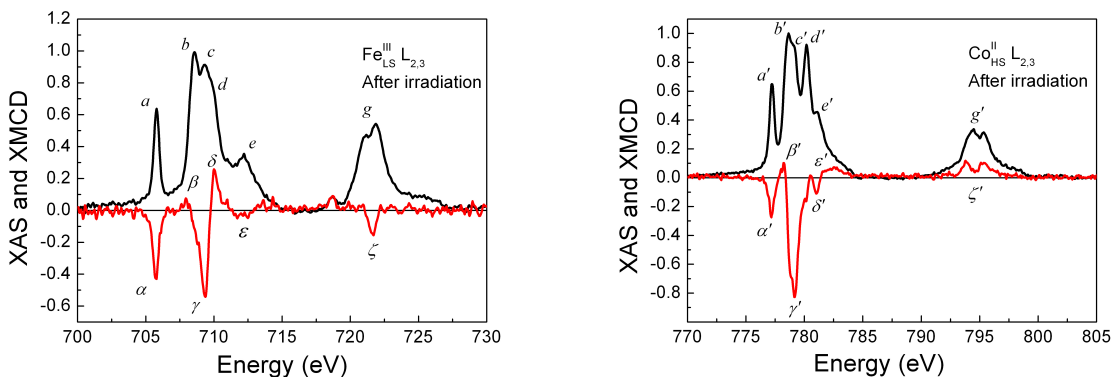


Figure 5: Experimental XAS (black line) and XMCD (red line) signals at the Co (left) and Fe (right) $L_{2,3}$ edges at $T = 2$ K and $\mathbf{B} = 6.5$ T after 660-nm irradiation, in compound **1**.

Fe spin magnetic moment can only be determined by LFM calculations or by comparison with reference XMCD data.⁷⁴ From the experimental XMCD signal recorded for **2** and from LFM calculations where the back-bonding character of the cyanido bonding is fully taken into account, it is determined by cross-multiplication that the orbit and spin magnetic moments of $\text{Fe}_{\text{LS}}^{\text{III}}$ in **1** are equal to $\approx 0.65 \mu_B$ and $\approx 0.53 \mu_B$, respectively (left panel of Figure S9 in Supporting Information). The XMCD signal at the Co $L_{2,3}$ edges is characterized by a large negative contribution γ' accompanied by two smaller negative ones α' and δ' , while the XMCD signal at the L_2 edge gives a small positive contribution. The intensity of the γ' peak is rather large and amounts to 83 % of the maximum of the Co L_3 edge spectrum. One thus expects a rather large magnetic moment carried by the Co ions with a significant contribution from the orbital magnetic moment. By comparison with LFM calculations, one finds that the orbital magnetic moment is $0.46 \mu_B$ and the spin magnetic one is $1.38 \mu_B$ per Co ion (Left panel of Figure S10 in Supporting Information).

For compound **1**, the magnetization curves detected by XMCD independently for Fe and Co ions are shown in Figure 6. They have been recorded by setting the monochromator at the maximum of the L_3 edge XMCD signals for Fe (at 709.33 eV) and Co (at 779.18 eV), ramping up and down the magnetic field between +5 and -5 T. The various magnetization branches have been properly averaged to yield the 0 to 5 T magnetization curve and have

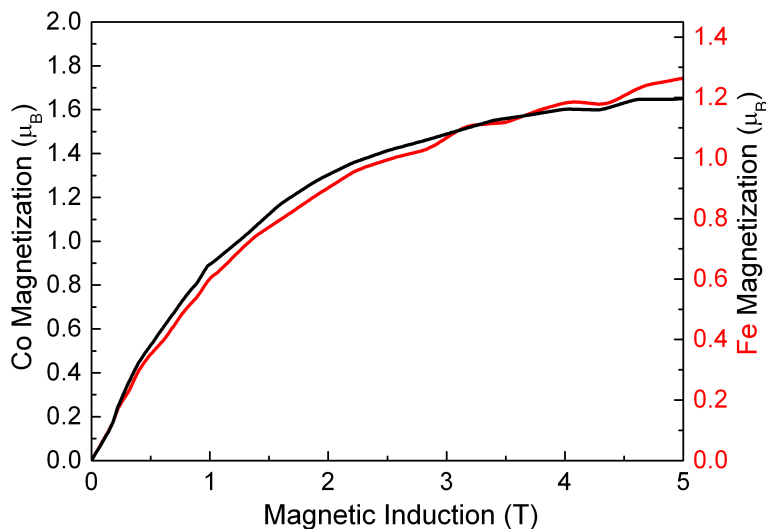


Figure 6: Field dependence of the maximum of XMCD signal at the L_3 edge for Fe (red line) and Co (black line). The XMCD intensity is converted into Bohr magnetons following the magnetic moment determination from Figure 5 (see text for more information).

been normalized in Bohr magnetons in agreement with the Fe and Co magnetic moments determined by XMCD. The magnetic saturation is not completely achieved for both Fe and Co ions and no detectable opening of the magnetization curves is observed. In addition, the shape of the magnetization curves are very similar for both Fe and Co, so that there is no sign of any antiferromagnetic coupling between the two ions at $T = 2$ K. It is not possible from the present set of magnetization curves to determine if the Fe and Co ions are ferromagnetically coupled or if they simply experience a similar magnetization under the action of the external magnetic induction.

Discussion

The present experimental results clearly evidence that the temperature-induced magnetic conversion between 300 and 100 K corresponds to an electron transfer that transforms the $\text{Fe}_{\text{LS}}^{\text{III}}\text{—Co}_{\text{HS}}^{\text{II}}$ paramagnetic pair into its $\text{Fe}_{\text{LS}}^{\text{II}}\text{—Co}_{\text{LS}}^{\text{III}}$ diamagnetic analogue. At lower temperature, around 4 K, the $\text{Fe}_{\text{LS}}^{\text{II}}\text{—Co}_{\text{LS}}^{\text{III}}$ diamagnetic pair can be transformed into the $\text{Fe}_{\text{LS}}^{\text{III}}\text{—Co}_{\text{HS}}^{\text{II}}$

paramagnetic pair under light irradiation. This result is fully in line with what is claimed by Koumoussi *et al.*³⁷ from conventional magnetic susceptibility measurements on the same system. Nevertheless, we want to stress that the present work reports the first direct evidence of the respective electronic state of Fe and Co ions at the atomic scale, and this for all the different phases involved in the switching mechanism. This conclusion is absolutely unambiguous since the spectral features associated to the XAS spectra at the $L_{2,3}$ edges of $\text{Fe}_{\text{LS}}^{\text{II}}$, $\text{Fe}_{\text{LS}}^{\text{III}}$, $\text{Co}_{\text{HS}}^{\text{II}}$ and $\text{Co}_{\text{LS}}^{\text{III}}$ are well documented in the literature from experimental reference spectra as well as from theoretical spectra calculated in the Ligand Field Multiplet model.^{42,55,71–73,79,80} In addition, the qualitative analysis of the features at the K edges support this conclusion although quantitative results are more difficult to extract.

At $T = 100$ K, it was found that the temperature-induced magnetic conversion was not complete. This is regularly observed when temperature- or light-induced conversions are observed by XAS at $L_{2,3}$ edges measured in TEY where the probing depth is less than 5 nm. Indeed, depending on the samples, Poneti *et al.* observed between 50 and 60 % of residual high temperature phase at 100 K,^{42,53,81} and Warner *et al.* observed between 10 and 55 % of residual depending on the sample thickness.⁴⁹ The temperature induced magnetic switching is possible when the environment of the Co ions allows enough flexibility so that the site can accommodate a $\text{Co}_{\text{HS}}^{\text{II}}$ to $\text{Co}_{\text{LS}}^{\text{III}}$ conversion.^{54,73,79} At the very surface of the measured sample, it is likely that the Co coordination sphere undergoes a partial reorganization that might prevent the temperature-induced electron transfer, explaining the observed residual contribution.

At 300 K and at 4 K after irradiation, **1** is composed of $\text{Fe}_{\text{LS}}^{\text{III}}-\text{Co}_{\text{HS}}^{\text{II}}$ paramagnetic pairs. From the comparison of both XAS spectra at the Fe $L_{2,3}$ edges, one can conclude that the electronic and local structures of Fe at 300 K is very similar to that at 4 K after irradiation (Figure 7, left panel). On the contrary, a similar comparison for the Co $L_{2,3}$ edges clearly indicates that the two $\text{Co}_{\text{HS}}^{\text{II}}$ spectra at 300 K and at 4 K are quite different: for the latter, feature **a'** is sharper, the intensities of features **b'** and **c'** are reversed and feature **e'** is larger

(Figure 7, right panel). These differences cannot originate from an incomplete photomagnetic conversion, since feature **a'** is more intense for the 4 K spectrum than for the 300 K one. They might arise either from a temperature dependence of the Co $L_{2,3}$ edges spectra or from local rearrangements around the Co ions similar to the ones observed for 3-D PBA molecule-based magnets.^{55,72,73,79} Therefore, XAS spectra were calculated in the Ligand Field Multiplet model for a $\text{Co}_{\text{HS}}^{\text{II}}$ ion in the same environment at 4 and 300 K, i.e. for the same set of crystal-field and spin-orbit parameters (Supporting Information Table S1). From Figure S11, it is clear that the calculations mimic fairly well the differences observed between the experimental Co XAS spectra for the two temperatures. On the basis of the LFM calculations, it can therefore be concluded that the parameters governing the electronic structure of $\text{Co}_{\text{HS}}^{\text{II}}$ ions such as spin-orbit coupling, crystal-field, and site distortion are likely identical in the 300 K paramagnetic phase and in the 4 K photo-induced phase. The difference in the electronic structure between 300 and 4 K stems from the different thermal population of the first excited states. This is in agreement with the K edge XAS and XRD results reported by Sekine *et al.* in cyanido-bridged FeCo square molecules where they confirmed that the electronic structure of the low temperature light-induced state is similar to the one of the high temperature state.^{43,59}

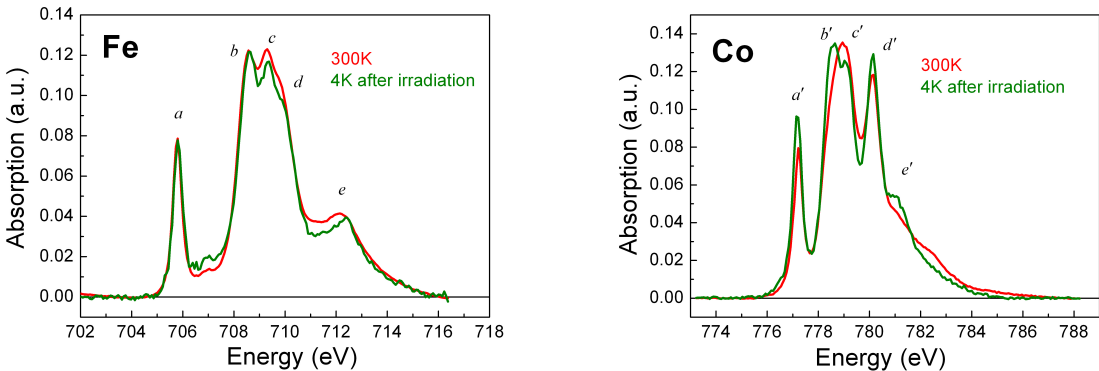


Figure 7: XAS spectra measured at the Fe (left) and Co (right) L_3 edges at 300 K before irradiation (red line) and at 4 K after irradiation (green line).

In Figure 6, the XMCD-detected magnetization curves for Fe and Co ions are superim-

posed. Within the uncertainty of the experimental measurement, there is no hint for an antiferromagnetic coupling between $\text{Fe}_{\text{LS}}^{\text{III}}$ and $\text{Co}_{\text{HS}}^{\text{II}}$ magnetic sites, in contrast to what has been suggested for similar systems.^{37,57,82} Since measurements have been performed at 2 K, our results indicate that the exchange coupling constant J between Fe and Co ions is such that $|J/k_B| \ll 1$ K (for $H = -2J \cdot \vec{S}_{\text{Fe}} \cdot \vec{S}_{\text{Co}}$).

In order to gain more information on the fine electronic structures of Fe and Co ions in the low temperature, photo-induced state, the XAS and XMCD signals from the two precursors (compounds **2** and **3**, see experimental section) of **1** were recorded at 2 K and in an external magnetic induction of 6.5 T. The Fe $L_{2,3}$ edges for compounds **1** and **2** are very similar (Figure S9). One observes the same series of spectral features, with mainly peak **a** that is characteristic of $\text{Fe}_{\text{LS}}^{\text{III}}$ and shoulder **e** that is a signature of Fe surrounded by 3 cyanido ligands. The intensity of features **b**, **c** and **d** are rather different as can be expected from the presence of the (Fe–CN–Co) bridge in **1**. The XMCD features are also very similar and almost homothetic for both samples. If one focuses on features **a** in the XAS spectra and α in the XMCD signals, the ratio α/a is 66 % for **1** while it is 70 % for its precursor **2**.⁷⁴ For compounds **1** and **3**, the situation is somewhat different at the Co L_3 edge. Indeed the local organization of the Co ions is very different in these compounds, so that both Co XAS spectra are quite different (Figure S10). In contrast, the two Co XMCD signals present similarities at the L_3 edge and rather large differences at the L_2 edge. The general shape is in agreement with what is expected for a hexacoordinated $\text{Co}_{\text{HS}}^{\text{II}}$ ion. One then concludes that at 6.5 T, the magnetizations of Fe and Co ions in **1** are quite similar to the magnetizations for isolated paramagnetic ions, as it is the case in **2** and **3**. This again confirms that the thermal fluctuations at 2 K are larger than any significant antiferromagnetic coupling between Fe and Co ions in **1**.

Conclusions

The electronic and magnetic structures of Fe and Co ions in a dinuclear photomagnetic PBA have been measured for the first time in an element selective way. Using a combination of XAS and XMCD spectroscopies supported by LFM calculations, our results prove unambiguously that **(i)** the 300 K phase and the light-induced excited state at 4 K are composed of $\text{Fe}_{\text{LS}}^{\text{III}}\text{—Co}_{\text{HS}}^{\text{II}}$ paramagnetic pairs and **(ii)** the 100 K phase is involving $\text{Fe}_{\text{LS}}^{\text{II}}\text{—Co}_{\text{LS}}^{\text{III}}$ diamagnetic pairs. From the LFM calculations, one can suggest that both paramagnetic phases at 300 K and at 4 K after light irradiation are identical, with no apparent major reorganization of the local structure either around Fe or Co. In the paramagnetic pairs at 2 K and under an external magnetic induction of 6.5 T, both Fe and Co ions exhibit rather large orbital magnetic moments: $0.65 \mu_B$ for Fe and $0.46 \mu_B$ for Co. For Fe ions, the orbital magnetic moment is larger than the spin magnetic moment as already observed for the $[\text{TpFe}(\text{CN}_3)]^-$ precursor, i.e. **2**.⁷⁴ The total magnetic moment of Co is larger than the Fe one and we do not observe any evidence of antiferromagnetic coupling between Fe and Co magnetic centers. The light induced excited state is relaxed at 50 K, so that at temperatures below 50 K, **1** presents a bistability that could be addressed by an appropriate application of light and temperature. XMCD measurements at very low temperature (around 200 mK)⁶¹ might help further characterizing the sign and magnitude of the magnetic coupling between Fe and Co metal ions.

Understanding the electron transfer mechanism in the dinuclear PBA **1** was a necessary first step before exploring whether this molecule or similar ones would preserve the electron transfer mechanism when isolated on surfaces. Such future studies could pave the way towards ultimate miniaturization.

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Supporting Information Available

XAS spectra at the $L_{2,3}$ edges showing the reversibility, XAS spectra measured at the Fe and Co K edges, XAS and XMCD spectra measured in the Fe and Co precursors, Co L_3 edge spectra calculated in the Ligand Field Multiplet model. This material is available free of charge via the Internet at <http://pubs.acs.org/>.

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Graphical TOC Entry

