

# Site-Selective Real-Time Observation of Bimolecular Electron Transfer in a Photocatalytic System Using L-Edge X-Ray Absorption Spectroscopy\*\*

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Time-resolved X-ray absorption spectroscopy has been utilized to monitor the bimolecular electron transfer in a photocatalytic water splitting system. This has been possible by uniting the local probe and element specific character of X-ray transitions with insights from high-level ab initio calculations. The specific target has been a heteroleptic  $[\text{Ir}^{\text{III}}(\text{ppy})_2(\text{bpy})]^+$  photosensitizer, in combination with triethylamine as a sacrificial reductant and  $\text{Fe}_3(\text{CO})_{12}$  as a water reduction catalyst. The relevant molecular

transitions have been characterized via high-resolution Ir L-edge X-ray absorption spectroscopy on the picosecond time scale and restricted active space self-consistent field calculations. The presented methods and results will enhance our understanding of functionally relevant bimolecular electron transfer reactions and thus will pave the road to rational optimization of photocatalytic performance.

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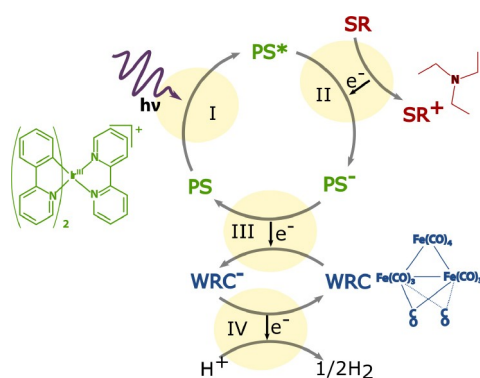
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## 1. Introduction

Water splitting has gained increased scientific interest in the past years as a sustainable source of carbon-free fuels, which could become a future alternative to the existing fossil-based sources.<sup>[1]</sup> In particular, solar light-induced catalytic splitting of water into hydrogen and oxygen is a very promising approach to generate hydrogen as a solar fuel, which undergoes combustion without producing undesired  $\text{CO}_2$ .<sup>[2]</sup> Applying catalysts allows to overcome the relatively high thermodynamical barriers associated with the chemical reaction steps leading to the evolution of oxygen and hydrogen.<sup>[3]</sup> In particular, homogeneous catalysis is rapidly emerging in this field, and various protocols for the generation of oxygen<sup>[4]</sup> and hydrogen<sup>[5]</sup> from water have been published. A key challenge in this area is the design of more efficient photosensitizers (PS) that absorb well visible light leading to charge-separated and long-lived electronically excited states.<sup>[6]</sup> The latter are typically associated with strong reductive and oxidative power and have to provide negative and positive charge with sufficient driving force for enabling water reduction (hydrogen generation) and oxidation (oxygen generation), respectively. Metalorganic complexes represent a very promising class of PSs since many of them feature rather long living metal-to-ligand charge transfer triplet ( $^3\text{MLCT}$ ) states and, therefore, are currently subject of intense research activities. While at the beginning ruthenium complexes were mostly applied, meanwhile, amongst others, iridium (Ir), copper, and iron complexes are broadly investigated. Iridium complexes such as the heteroleptic complex  $[\text{Ir}^{\text{III}}(\text{ppy})_2(\text{bpy})]^+$  (where ppy = 2-phenylpyridine and bpy = 2,2'-bipyridine), turned out to be promising candidates for PSs in water splitting.<sup>[7,8]</sup> Gärtner et al. reported that this Ir-based PS (IrPS) results, in combination with iron carbonyl complexes as

catalysts, in efficient homogenous systems for photocatalytic hydrogen generation.<sup>[9]</sup> Under optimized conditions exceptionally high internal quantum yields exceeding 40% were achieved.<sup>[10,11]</sup> The work on copper, iron, and other non-precious metals is driven by the goal to replace the rare noble metals by more abundant and less expensive elements. In the case of iron PSs the research is still focused on the design of complexes with suitable long-lived MLCT states.<sup>[12–14]</sup> Promising results in photocatalytic water reduction were already reported for homogeneous photocatalytic systems based on Cu(I) PS complexes as well as on zinc porphyrins.<sup>[15–17]</sup> However, all systems are still far from being applied in the real world due to their insufficient performance. Detailed mechanistic studies applying operando methods and stationary as well as time-resolved spectroscopy are performed in order to understand the individual reaction steps, the microscopic mechanisms, and performance limiting factors and to provide in this way guidelines for a better system design.<sup>[18–20]</sup> Systems based on IrPSs are particularly well suited for such investigations since they show high yields and several spectroscopic experiments provide already a solid data base for the interpretation of results obtained by more sophisticated approaches.<sup>[11,21–23]</sup>

Along this line we present the application of a suite of complementary time-resolved (TR) hard X-ray spectroscopies with picosecond (ps) temporal resolution, in combination with ab initio electronic structure calculations to study a fully functional photocatalytic system for solar hydrogen generation (Figure 1). It includes triethylamine (TEA) acting as a sacrificial reductant (SR) that quenches the photoexcited  $[\text{Ir}^{\text{III}}(\text{ppy})_2(\text{bpy})](\text{PF}_6)$  and a  $\text{Fe}_3(\text{CO})_{12}$  complex as the water reduction catalyst. Our study aims to complete the current picture<sup>[22,24]</sup> of the influence of geometric and/or electronic structures of long-lived ( $>100$  ps) charge-separated excited states on the system's performance. This includes the efficiency of light-harvesting, subsequent reductive quenching of the IrPS by the SR molecules, and the intermolecular electron transfer to the water reduction catalyst (WRC). A deeper understanding of the structure-function relationship is critical for the develop-

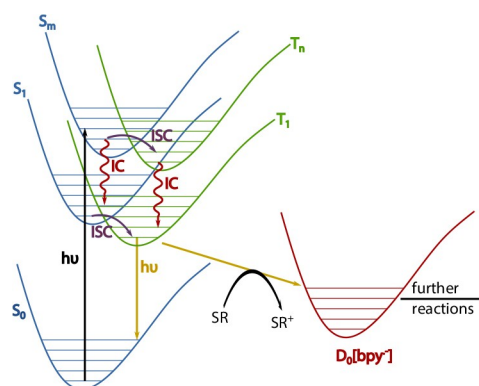


**Figure 1.** Reaction cycle of a photocatalytic system consisting of a homogeneous solution of a sacrificial reductant (SR), a photosensitizer (PS) and a water reduction catalyst (WRC) for solar hydrogen generation [21, 25, 9, 22, 24]. The system discussed here consists of the PS  $[\text{Ir}^{\text{III}}(\text{ppy})_2(\text{bpy})]^+$ , triethylamine (TEA) as the SR and  $\text{Fe}_3(\text{CO})_{12}$  as the WRC.

ment and optimization of PS complexes for efficient hydrogen production in molecular photocatalysis.

The function of this system and its constituents has been described previously in Refs. [21,24–26], cf. Figure 1. It involves a four-step process, in which the Ir-based PS absorbs a photon and is excited to an electronically excited state  $\text{PS}^*$  (step I), which can be subsequently reduced by an electron transfer from a TEA molecule yielding  $\text{PS}^-$  (step II). The next step involves another electron transfer to the WRC (step III), which then reduces a proton of a nearby  $\text{H}_3\text{O}^+$  molecule to hydrogen (step IV). The photocatalytic reaction steps reported here are initiated by excitation in the intense metal-to-ligand charge transfer (MLCT) bands in the near UV range around 350 nm. The complete UV-Vis absorption spectrum of the IrPS complex is shown in Figure S1 of the Electronic Supplementary Information (ESI).

The photophysical and -chemical processes in IrPS, which take place upon the excitation into the singlet MLCT band at 355 nm are summarized in Figure 2. The photoexcitation of the molecule occurs within the Franck-Condon regime from the singlet ground state  $S_0$  to a singlet MLCT state labeled  $S_m$ . The lowest excited bright state corresponds to a  $\pi d_{x^2-y^2} \rightarrow \pi^*(\text{ppy})$  electronic transition.<sup>[27,28]</sup> Excitation is followed by an ultrafast relaxation via internal conversion (IC) and intersystem crossing (ISC) into the lowest triplet MLCT state of  $\pi d_{x^2-y^2} \rightarrow \pi^*(\text{bpy})$  character labeled  $T_1$ . Recently, ISC rates for similar Ir(III)-complexes were measured using femtosecond optical transient absorption spectroscopy<sup>[29]</sup> and TR photoluminescence measurements.<sup>[29,30]</sup> It was found that the ISC and relaxation into  $T_1$  state occurs within 70–100 fs. This triplet state has a long lifetime, which can be chemically tuned from some hundreds of nanoseconds to several microseconds.<sup>[9]</sup> Once in the long-lived  $T_1$  state, the IrPS can be reduced to a doublet  $D_0$  state by the SR and the excess electron residing on the  $\pi^*(\text{bpy})$  orbital<sup>[28]</sup> can be transferred from the  $\text{PS}^-$  complex to the WRC, as shown in step III in Figure 1. As a competing mechanism to the reduction, a radiative or non-radiative deactivation of the  $T_1$  back into the ground state can occur. The photoluminescence lifetimes of the  $T_1$  state in tetrahydrofuran (THF) solution both with and without



**Figure 2.** Potential energy surface scheme of the relevant potentials as well as the photophysical and -chemical reactions of  $[\text{Ir}(\text{ppy})_2(\text{bpy})]^+$ , adapted from Ref. [24]. In the present study we focus on the dynamics of the reactive  $T_1$  state and in particular the electron transfers involving the IrPS.

the SR (present as a co-solvent in a THF/TEA mixture with a 5/1 volume ratio) were measured to be 13 ns and 370 ns, respectively.<sup>[22]</sup>

A complete study of the underlying photoinduced dynamics and more importantly the mechanistic aspects governing these processes at the PS and the WRC sites is often severely hindered when using only optical methods, since they are not sensitive to the oxidation state of the central metal ion and the molecular geometric structure. On the contrary, employing ultrafast X-ray spectroscopies allows accessing in an element-specific manner the active sites, i.e. the different metal ions, and to capture the transient electronic and geometric structure changes occurring during the photocatalytic function of the system.

The present study is motivated by early pump-probe X-ray absorption spectroscopy (XAS) studies, in which the oxidation states<sup>[31,32]</sup> and local geometric structures<sup>[31–33]</sup> of liquid-phase molecular systems have been investigated. Later, TR XAS has been used to investigate the triplet excited state of the Ir model system Ir(ppy)<sub>3</sub><sup>[34]</sup> and the combination with DFT allowed the study of this excited state of a pure solvated Ir photosensitizer.<sup>[35]</sup> Picosecond- and femtosecond-resolved X-ray studies of a bimetallic donor-acceptor Ru–Co complex (a prototypical photocatalytic system) have shown how ultrashort hard X-ray spectroscopies can be efficiently used to follow both the intra- and intermolecular charge transfer processes at the optically silent sites of photocatalysts.<sup>[36,37]</sup> In a similar study, pump-probe XAS, paired with all-optical experiments, was used to investigate intramolecular electron transfer processes in a whole family of homo- and heterodinuclear Cu(I)/Ru(II) complexes.<sup>[38]</sup> The applicability of high-energy resolution fluorescence detection (HERFD)<sup>[39]</sup> XAS as well as X-ray Emission Spectroscopy (XES) to answer questions in catalysis has been further demonstrated using Fe complexes.<sup>[40]</sup> In very recent experiments, the structural and electronic configurations of a Co<sup>[41]</sup> and Ni<sup>[42]</sup> proton reduction catalyst were characterized.

By a similar approach we investigate here the primary electron transfer step that is experienced by the IrPS [Ir<sup>III</sup>(ppy)<sub>2</sub>(bpy)]<sup>+</sup> in the above introduced photocatalytic system after optical excitation. The goal is to characterize the electronic configuration of the IrPS prior and after the electron transfer event and to identify the involved orbitals in order to obtain a validated microscopic picture of this crucial step.

## Experimental Measurements

Time-resolved spectra of the X-ray absorption near edge structure (XANES) of [Ir(ppy)<sub>2</sub>(bpy)]<sup>+</sup> were collected at the 7ID–D beamline of the Advanced Photon Source (APS) both in total fluorescence yield (TFY) as well as in the HERFD mode. More details concerning the experimental setup and the pump-probe techniques available at this beamline can be found in Refs [33,43,44]. Here we will only briefly summarize the experimental conditions present during the pump-probe measurements, which allowed us to record high quality X-ray absorption and X-ray emission spectra of both the ground and excited states of the IrPS complex. The APS in 24 bunch mode delivered an average X-ray flux of  $4 \times 10^{11}$  photons/s at the Ir L<sub>3</sub>-edge (11.2 keV) in pulses with a repetition rate of 6.5 MHz. The X-

ray probe pulses were monochromatized to  $\Delta E/E = 5 \times 10^{-5}$  and focused to a spot of  $4 \times 5 \mu\text{m}^2$  on the sample consisting of the sample solution in a 100  $\mu\text{m}$  thick free flowing liquid jet. The optical pump laser repetition rate was set to 931 kHz, i.e. the 7<sup>th</sup> sub-harmonic of the X-rays. The inter-pulse spacing of 1.07  $\mu\text{s}$  allows for a full ground state recovery between consecutive laser pulses. The laser wavelength was frequency tripled to 355 nm and laser pulses with 142 nJ energy were used to excite the sample. The laser focus was set to  $13 \times 21 \mu\text{m}^2$ , thus slightly larger than the X-ray spot size, leading to a laser peak intensity of 6.6 GW/cm<sup>2</sup>. TFY XAS were measured using a scintillation detector. Simultaneously HERFD XAS were acquired to obtain XAS with sub core-hole lifetime limited energy resolution, which in simplified words works as follows: X-ray absorption spectra measured in total fluorescence yield are broadened by a total Lorentzian lifetime broadening  $\Gamma = \Gamma_L + \Gamma_M$ , where  $\Gamma_L$  and  $\Gamma_M$  are the lifetime widths of the intermediate and final states, in our case with an L-shell and M-shell core-hole, respectively. The intermediate state lifetime broadening  $\Gamma_L$  can be partially eliminated by using a detection method with a resolution better than  $\Gamma_L$ .<sup>[39]</sup> The HERFD XAS were measured with a Johann<sup>[45]</sup> spectrometer employing a Ge(800) analyzer crystal to selectively detect photons at the L $\alpha_1$  peak energy of 9175 eV. Three different sample solutions were measured: i) 15 mM of pure IrPS in CH<sub>3</sub>CN, ii) 15 mM of IrPS in a 1:4 mixture of TEA and CH<sub>3</sub>CN and iii) 12.5 mM IrPS and 9 mM Fe<sub>3</sub>(CO)<sub>12</sub> in a 1:5 mixture of TEA and CH<sub>3</sub>CN. Here, CH<sub>3</sub>CN is chosen as solvent since it is, in contrast to the THF used in the optimized catalytic system, not considered a possible carcinogen. It was previously shown that the photocatalytic system works also with CH<sub>3</sub>CN as solvent, however, with lower yields.<sup>[10]</sup> The high IrPS concentration is necessary due to the thin sample thickness.

Ultrafast optical absorption studies as well as time-resolved luminescence measurements were already performed on IrPS dissolved in acetonitrile.<sup>[23]</sup> They showed that also in this Ir complex the MLCT state is populated within the first 100 fs and the lifetime of its luminescence amounts to 60 ns. Since these experiments were carried out with air-saturated samples it was advantageous for a comparison on common ground to use also in the present experiments air-saturated solutions.

## Theoretical Calculations

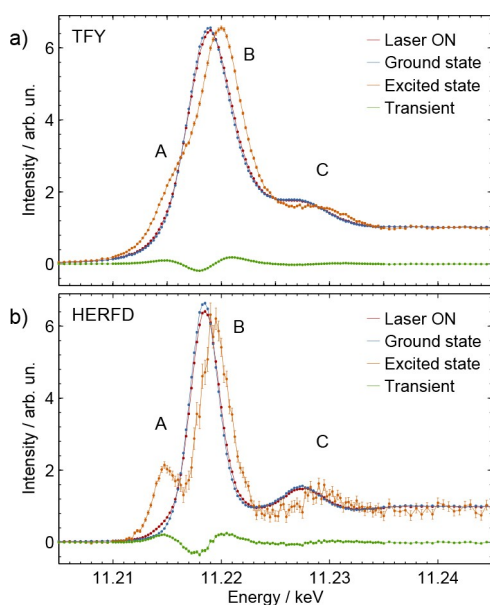
X-ray spectra originating from the ground singlet S<sub>0</sub> and first excited triplet T<sub>1</sub> electronic states were calculated in the dipole approximation at the first principles restricted active space self-consistent field (RASSCF) level and perturbative LS-coupling scheme for the spin-orbit coupling.<sup>[46,47]</sup> This method, due to its correlated nature, is a prerequisite to describe X-ray absorption resulting from excited states (here T<sub>1</sub>). A relativistic ANO-RCC basis set<sup>[48,49]</sup> of triple-zeta quality for iridium and its first coordination shell and of double-zeta quality for other atoms was employed. For the detailed description of the protocol, see e.g. Ref. [50]. The complex has a low C<sub>2</sub> point group symmetry. Thus, we prefer not to use octahedral symmetry labels. The active space comprised three Ir 2p, two pairs of highly correlated bonding  $\sigma$ d and antibonding  $\sigma^*$ d orbitals, the  $\pi$ d<sub>x<sup>2</sup>-y<sup>2</sup></sub> orbital, two mainly non-bonding d<sub>xz</sub> and d<sub>yz</sub> orbitals, and one  $\pi^*$ (bpy) orbital (see Figure 5b)). This allows for the description of the S<sub>0</sub> and T<sub>1</sub> states (originating from  $\pi$ d<sub>x<sup>2</sup>-y<sup>2</sup></sub>  $\rightarrow$   $\pi^*$ (bpy) excitation) as well as of the Ir L-edge core excited states. The influence of solvent was not taken into account. This setup should provide reliable results for transition metal compounds, where static electron correlation could play an important role.<sup>[27]</sup> Spectra were calculated at the equilibrium geometries of the S<sub>0</sub> and T<sub>1</sub> states taken from Ref. [27]. Molecular orbital energies were obtained using long-range corrected density

functional theory (LC-BLYP with a LANL2DZ/6-31G(d) basis set)<sup>[51]</sup> since RASSCF does not provide energies of canonical orbitals.

## 2. Results and Discussion

Figure 3 shows the TFY and HERFD XANES spectra of bare IrPS in CH<sub>3</sub>CN (i.e. in absence of TEA and WRC) with and without laser excitation, as well as the transient difference between laser excited and GS and the reconstructed excited state spectrum. The spectrum of the laser excited sample (Laser ON) was determined to contain an excited state fraction of 12%. This is used to reconstruct the excited state (ES) spectrum by removing the remaining (dominant) contribution of the ground state (GS) from the laser excited spectrum. See ESI for details on the determination of the excited state fraction and the reconstruction of the excited state spectrum.

The features of the TFY spectra are extremely broad due to the 5.25 eV L<sub>3</sub>-edge core-hole lifetime broadening.<sup>[52]</sup> The HERFD spectra show the same features as the TFY spectra, however, with a by about 2 eV improved resolution of 3.0–3.5 eV. Thus



**Figure 3.** L<sub>3</sub>-edge XANES spectra measured in a) TFY and b) HERFD of the laser excited ensemble (red), the ground state (blue), the reconstructed excited state (orange) and the transient difference between laser excited and GS (green) of Ir[(ppy)<sub>2</sub>(bpy)]<sup>+</sup> in CH<sub>3</sub>CN.

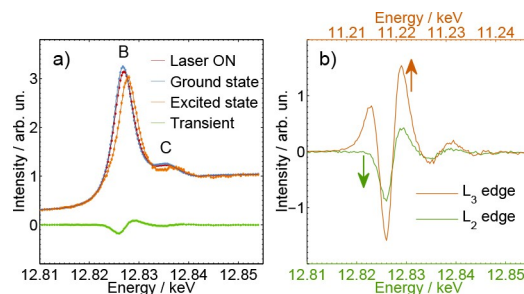
**Table 1.** Upper panel: Energies of L<sub>3</sub>-edge XANES features, all energies are given in eV relative to the 2p<sub>3/2</sub> ionization energy of 11215 eV. Lower panel: Energies of L<sub>2</sub>-edge XANES features, all energies are given in eV relative to the 2p<sub>1/2</sub> ionization energy of 12824 eV.

	A	B	C	edge
Ground state (L <sub>3</sub> )		3.8 ± 0.1	12.8 ± 0.3	5.4 ± 1.6
Excited state (L <sub>3</sub> )	0.2 ± 0.2	4.8 ± 0.3	14.7 ± 0.4	6.4 ± 8.8
Shift GS-ES (L <sub>3</sub> )		+1.0 ± 0.4	+1.9 ± 0.5	+1.0 ± 9.0
Ground state (L <sub>2</sub> )		2.7 ± 0.1	11.7 ± 0.1	4.5 ± 1.1
Excited state (L <sub>2</sub> )	-0.8 ± 0.4	3.7 ± 0.2	13.4 ± 0.3	5.7 ± 3.3
Shift GS-ES (L <sub>2</sub> )		+1.0 ± 0.3	+1.7 ± 0.4	+1.2 ± 3.5

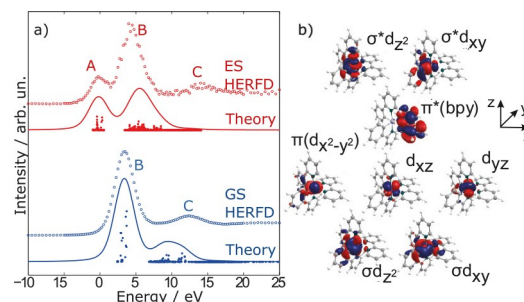
for the further analysis we focus on the HERFD spectra in Figure 3b). The prominent features of the spectra are labeled A, B and C, cf. Table 1. In the GS spectrum a very intense white line feature B around 11.219 keV and a second transition C at higher energy of about 11.229 keV are visible. The ES spectrum contains an additional peak A at a lower energy of about 11.215 keV, which is not visible in the GS spectra. Furthermore, B and C shift about 1 eV – 2 eV to higher energies in the ES compared to the GS, thus evidencing the oxidation of the Ir center from Ir<sup>III</sup> to Ir<sup>IV</sup>.

The L<sub>2</sub>-edge measured in TFY is presented in Figure 4a) and exhibits the same features in the GS as the L<sub>3</sub>-edge. However, in the ES the feature A is not clearly visible, only an extremely weak shoulder could potentially be observed here. Even when comparing the transient differences of the GS and the ES (see Figure 4b)), in the L<sub>2</sub>-edge the first positive peak, which is very pronounced in the L<sub>3</sub>-edge, is not present.

The assignment of the L<sub>3</sub>-edge features is made on the basis of RASSCF calculations. The comparison of the experimental and theoretical spectra for both ground and excited states can be found in Figure 5a). The spectrum consists of several tens of transitions with non-zero intensity. Some of them have minute contributions but sum up to a notable feature due to their number. The assignment of multi-reference many-body RASSCF



**Figure 4.** a) TFY L<sub>2</sub>-edge XANES of the laser excited ensemble (red), the reconstructed excited state (orange), the ground state (blue) and the transient difference between laser excited and GS (green) of Ir[(ppy)<sub>2</sub>(bpy)]<sup>+</sup> in CH<sub>3</sub>CN. In b), a comparison between this L<sub>2</sub>-edge transient (green) to the L<sub>3</sub>-edge transient (orange) is shown, the transients are normalized to the respective edge jump and scaled to 100% excited state fraction.



**Figure 5.** a) Simulated (theory) and measured HERFD L<sub>3</sub>-edge XANES of the S<sub>0</sub> GS (blue, bottom) and the T<sub>1</sub> MLCT ES (red, top). The x-axis is given relative to the 2p<sub>3/2</sub> ionization energy of 11215 eV, features A, B and C are labeled as in Figure 3. b) Orbital active space (apart from 2p orbitals) used for the RASSCF calculations.



wave functions is quite involved due to their multiconfigurational character, which is additionally complicated by spin-orbit coupling. Here, for simplicity, the information is reduced to transitions between single orbitals (Figure 5b)), having however non-integer occupations. An orbital energy scheme for the relevant transitions discussed in the following is given in Figure 6).

The GS spectrum contains two features denoted as B and C in Figure 5a) (blue line). Peak B mainly consists of  $2p \rightarrow \sigma^*d_{z^2}$  and  $2p \rightarrow \sigma^*d_{xy}$  transitions. Remarkably, some of the transitions having non-vanishing intensity are of  $2p \rightarrow \pi^*(bpy)$  nature and can be considered as charge-transfer excitations. Peak C in turn is due to two-electron shake up transitions, where in the region of 7–10 eV  $2p \rightarrow \sigma^*d_{z^2}$  transitions are occurring simultaneously with excitations from  $\pi d_{x^2-y^2}$  and  $d_{xz}$  orbitals to  $\pi^*(bpy)$  ones. Transitions in the 10–13 eV range are very similar but in this case  $\sigma^*d_{xy}$  is accepting the electron instead of  $\sigma^*d_{z^2}$ .

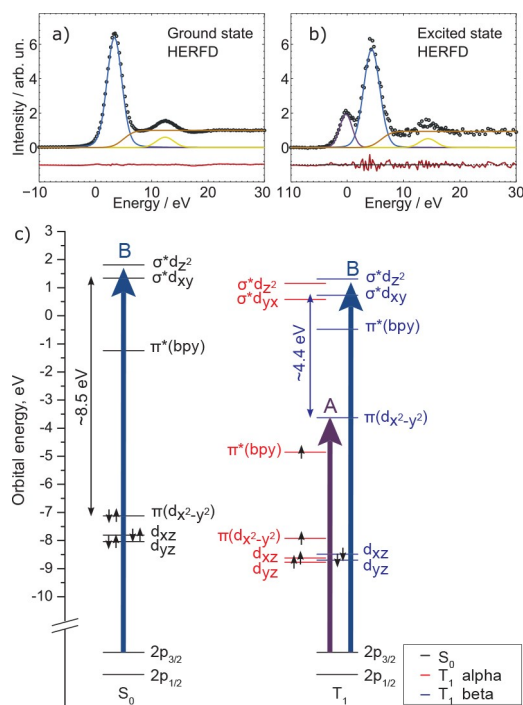
Features in the  $T_1$  spectrum have similar nature as those of the ground state spectrum with the only difference that the triplet configuration has a hole in the  $\pi d_{x^2-y^2}$  orbital and an additional electron in the  $\pi^*(bpy)$  orbital. This fact gives rise to an additional feature A in the excited state spectrum where transitions correspond mainly to  $2p \rightarrow \pi d_{x^2-y^2}$  excitation. This

assignment is in agreement with that reported for the higher symmetric homoleptic  $[Ru(bpy)_3]^{2+}$  complex.<sup>[31]</sup> The main type of transitions contributing to feature B is of  $2p \rightarrow \sigma^*d_{z^2}$  and  $2p \rightarrow \sigma^*d_{xy}$  nature. In addition to shake ups mentioned above, one sees also contributions from  $d_{xz,yz} \rightarrow \pi d_{x^2-y^2}$  and  $\pi^*(bpy) \rightarrow \sigma^*d_{xy}$  transitions because of the additional hole/electron present in the  $T_1$  state. Interestingly, the low-energy flanks of the bands A and B in the  $T_1$  spectrum have mainly spin-forbidden character gaining intensity due to spin-orbit coupling. This means that the initial state is mostly triplet, while the final ones are predominantly singlet. According to the calculations, the  $2p_{1/2} \rightarrow \pi d_{x^2-y^2}$  transitions corresponding to the A feature in the  $L_2$  band are not energetically separated from the transitions constituting the B band. Moreover, they have a significantly lower intensity than for the  $L_3$ -edge. Both energetic blue shift and low intensity are due to the notable two-electron excitation character of the respective states, making them a mixture of the main and shake-up transitions.

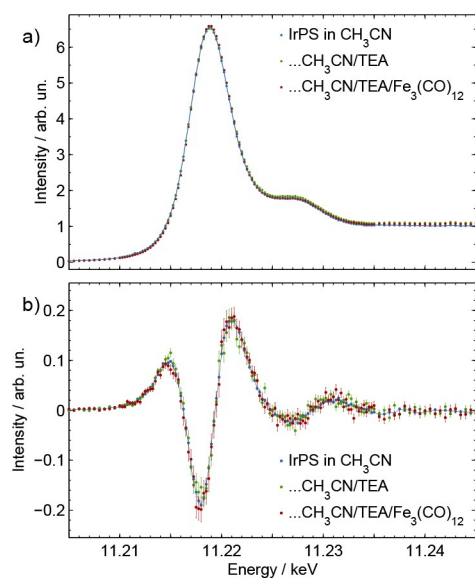
To further quantify the exact energy positions of the XAS features, the HERFD XANES spectra have been fitted using a superposition of an arctan-broadened absorption edge and Voigt profiles for the discrete transitions. The corresponding bands of the fit are shown in Figure 6a) and b) and the peak and edge position obtained from this fit can be found in Table 1. The same fitting procedure was also applied to the  $L_2$ -edge TFY XAS (see ESI). Here, although not clearly visible at first sight, also a transition A had to be included. The obtained energies of the respective features are added to the table. The energy shift between the A and B transitions reflects the energy difference between the  $\pi d_{x^2-y^2}$  and the two  $\sigma^*$  orbitals of ( $4.6 \pm 0.4$ ) eV which is within the error bars also confirmed by the respective features of the  $L_2$ -edge. The splitting is in good accord with the theoretical value reported in Figures 5a and 6c. Most importantly for the application of the time-resolved XAS measurements to the catalytic hydrogen production process, we are able to determine the occupation of the 5d-orbital and to monitor the optically induced charge separation with concomitant creation of a vacancy in the 5d-shell. This should in the next step allow for monitoring the arrival of an additional charge from the SR to the  $PS^*$ .

The static TFY XANES spectra of the IrPS in  $CH_3CN$ , of the IrPS in the TEA/ $CH_3CN$  mixture and of the IrPS in the mixture together with the WRC  $Fe_3(CO)_{12}$  are indistinguishable within our experimental accuracy, see Figure 7. This allows us to conclude that the addition of the SR as well as of the WRC does not severely affect the geometric or electronic structure of the IrPS in the GS. The transient TFY XANES of all three samples after optical excitation are qualitatively similar as well, thus 100 ps after photoexcitation the IrPS is presumably in the same electronic state independent of the SR and the WRC.

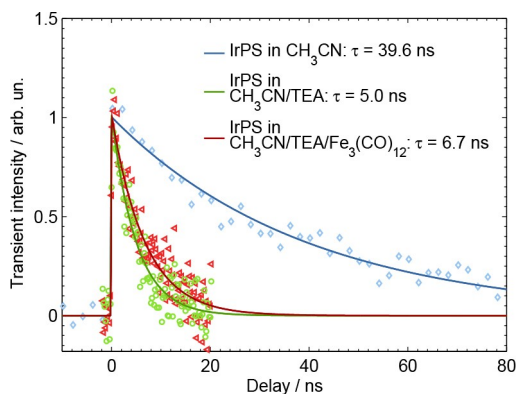
Time delay scans of the excited state of these three samples have been taken at the energy of maximum transient intensity, i.e. at 11221.5 eV (see Figure 8). A fit of a convolution of a Gaussian broadened step function with an exponential decay delivered MLCT excited state lifetimes of ( $39.6 \pm 2.8$ ) ns, ( $5.0 \pm 0.6$ ) ns and ( $6.7 \pm 0.7$ ) ns for the IrPS in  $CH_3CN$ , the IrPS in the



**Figure 6.** Reconstructed HERFD XANES spectra together with measured data of  $[Ir(ppy)_2(bpy)]^+$  in  $CH_3CN$  in its GS a) and ES b). The x-axis is given relative to the  $2p_{3/2}$  ionization energy of 11215 eV. c) Diagram showing the relevant orbitals as computed with restricted ( $S_0$ ) and unrestricted ( $T_1$ ) density functional theory. The orbital manifold of the  $T_1$  state contains two subsets:  $\alpha$  orbitals occupied by spin-up electrons (red) and  $\beta$  ones with spin-down electrons (blue) which have different energies. The transitions of the  $L_3$ -edge for the GS involve the orbitals  $2p_{3/2}$ ,  $\sigma^*d_{z^2}$ , and  $\sigma^*d_{xy}$  (blue arrow band B) and for the ES additionally transition to spin-down  $\pi d_{x^2-y^2}$  (purple arrow, band A). The  $L_2$ -edge XANES contains the corresponding transitions starting from the  $2p_{1/2}$  sub-shell (not shown with arrows).



**Figure 7.** Comparison of the TFY yield  $L_3$ -edge XANES of  $[\text{Ir}(\text{ppy})_2(\text{bpy})]^+$  in  $\text{CH}_3\text{CN}$  (blue), as well as in  $\text{CH}_3\text{CN}/\text{TEA}$  (green) and in  $\text{CH}_3\text{CN}/\text{TEA}/\text{Fe}_3(\text{CO})_{12}$  (red) mixtures, respectively. In a) the ground state spectra and in b) the transient differences 100 ps after excitation are shown. The static spectra and the transient differences are arbitrarily scaled in intensity to simplify comparison.



**Figure 8.** Time delay scan of the transient difference XANES intensity at 11221.5 eV of  $[\text{Ir}(\text{ppy})_2(\text{bpy})]^+$  in  $\text{CH}_3\text{CN}$  (blue), as well as in  $\text{CH}_3\text{CN}/\text{TEA}$  (green) and  $\text{CH}_3\text{CN}/\text{TEA}/\text{Fe}_3(\text{CO})_{12}$  (red) mixtures. A fit of an exponential decay represents the excited state lifetimes of  $(39.6 \pm 2.8)$  ns,  $(5.0 \pm 0.6)$  ns and  $(6.7 \pm 0.7)$  ns for the three samples, respectively.

$\text{TEA}/\text{CH}_3\text{CN}$  mixture and the IrPS together with the  $\text{Fe}_3(\text{CO})_{12}$  in the  $\text{TEA}/\text{CH}_3\text{CN}$  mixture, respectively. The ground state recovery time of  $(39.6 \pm 2.8)$  ns is similar, but slightly shorter than the previously reported luminescence decay time of 60 ns, which is supposed to reflect the depopulation of the MLCT state into the ground state.<sup>[23]</sup> The shorter ground state recovery could be due to the relatively high concentration of IrPS leading to self-quenching. The lifetime shortening associated with the addition of TEA by a factor of 8 is due to the electron transfer (ET) from TEA to the IrPS, see step II in Fig. 1. The MLCT state is clearly observed via the appearance of the A feature and the shift of the strong B transition upon optical excitation and the

associated depopulation of the  $\pi d_{x^2-y^2}$ -orbital. The lifetime of this transiently formed  $\text{Ir}^{\text{IV}}$  center of the MLCT state is probed representatively at the B-feature, although a more intuitive probe for future experiments could be to directly monitor the  $\pi d_{x^2-y^2}$ -orbital filling via the A feature. Furthermore, the observed changes in the spectral features can be mainly attributed to the change in the oxidation state of Ir, and are not sensitive to the additional electron residing on the bpy ligand after the ET from TEA. This is supported by theory as  $\pi^*(\text{bpy}) \rightarrow \sigma^* d_{x^2-y^2}$  and  $\sigma^* d_{xy}$  transitions as a rule have negligible intensity. The slightly longer excited state lifetime of 7 ns in the fully functionally photocatalytic system can be attributed to the lower TEA concentration. Also in the presence of the WRC, the electron transfer from TEA is responsible for filling the hole at the Ir atom and oxidative quenching plays no role. Using the ES lifetime  $\tau_0$  without and  $\tau$  with the TEA present we can estimate the TEA concentration  $c_{\text{TEA}}$  dependent quenching rate constant  $k_q$  of the ES via ET using the Stern-Volmer equation<sup>[53]</sup>

$$k_q(c_{\text{TEA}}) = \frac{1}{\tau} - \frac{1}{\tau_0} \approx 1.76 \times 10^8 \text{ s}^{-1}. \quad (1)$$

With the TEA concentration  $c_{\text{TEA}} = 1.44 \text{ M}$  this results in a bimolecular quenching ET rate of  $k_{\text{ET}} = 1.22 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$ . The ET rate for a diffusion limited reaction is estimated to  $2.06 \times 10^{10} \text{ M}^{-1} \text{ s}^{-1}$  (see ESI for details). The estimate of both the quenching rate constant and the diffusion limited ET rate rely on the prior knowledge that the reaction is of first order,<sup>[22]</sup> for a more rigorous analysis, multiple data points at distinct TEA concentrations should be taken. According to the findings, only about every 170th encounter of a TEA molecule with an excited IrPS leads to an electron transfer process.

The results are well in line with previous findings obtained by time-resolved photoluminescence measurements on the IrPS. In that case quenching of the sensitizer phosphorescence by TEA was studied in tetrahydrofuran solutions.<sup>[22]</sup> A bimolecular quenching rate of  $5.9 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$  was observed while the diffusion controlled collision rate was estimated to  $1.4 \times 10^{10} \text{ M}^{-1} \text{ s}^{-1}$  indicating that only one out of 200 collisions results in a quenching event. This is in good agreement with the ET efficiency found in the present experiments. In the previous study also ab initio calculations on the collision complex were performed.<sup>[22]</sup> They indicate that only at specific collision geometries an ET is possible and only a small fraction of the collisions occurs with such a geometry. This can explain the small number of encounters resulting in ET. The advantage of the present measurements is that not only depopulation of a luminescent state is observed but rather a transiently generated  $\text{Ir}^{\text{IV}}$  center, as part of the MLCT excited state, and the subsequent electron transfer from TEA to the  $5d$ -orbital of Ir, changing its oxidation state back to +3, thus proving the proposed ET pathway.

### 3. Conclusions

We have applied picosecond-resolved X-ray spectroscopies to investigate an Ir-based PS for photocatalytic hydrogen generation. We were able to quantify the electronic structural changes of the PS as they take place during the photocatalytic cycle by mapping the (metal centered) unoccupied orbitals of the IrPS in ground and excited states using mainly  $L_3$ -edge XANES. The features in the TFY spectra are extremely broadened due to the  $>5$  eV core-hole lifetime and applying HERFD XANES enabled an improvement in resolution of about 2 eV down to 3.0 eV–3.5 eV. This allowed for an accurate analysis of the XANES features and decomposing the edge into its main transitions, i.e. to accurately determine their energy positions and relative intensities. The detailed analysis was guided by high-level *ab initio* calculations of ground and excited state spectra. Equipped with this knowledge about relevant X-ray fingerprints, the IrPS in the fully functioning photocatalytic system was investigated. Here, we were able to directly observe the bimolecular electron transfer process from TEA to the IrPS via a reduction of the MLCT excited state lifetime of the IrPS by a factor of about 8. More specifically, we can monitor the oxidation state of the Ir atom. After optical excitation and trapping in the MLCT state, the  $\text{Ir}^{\text{III}}$  ion is oxidized to  $\text{Ir}^{\text{IV}}$  leading to the appearance of a new band in the X-ray absorption spectrum. Upon bimolecular electron transfer from the sacrificial reductant the hole on the Ir 5d shell is refilled, yielding back  $\text{Ir}^{\text{III}}$  and its characteristic spectrum. Due to the element specificity the extra electron on the bpy ligand does not yield noticeable changes in the Ir L-edge spectrum. Hence, the present setup is not sensitive to the electron relay from the IrPS to the WRC. Therefore, in future studies it would be desirable to also apply time-resolved X-ray absorption and emission at the Fe-edges of the WRC ( $\text{Fe}_3(\text{CO})_{12}$ ) to monitor also the last steps (III and IV) of the reaction cycle.

To summarize, the present proof-of-principle study has enhanced our understanding of functionally relevant bimolecular electron transfer reactions and thus will pave the road to rational optimization of the performance of homogeneous photocatalytic systems.

### Author Contributions

WG, CB, OK, SL and AB designed the research; NR and HJ synthesized the sample; NR, HJ and MB contributed to the conception; GD, AMM and SHS built the high-repetition rate pump-probe X-ray spectroscopy setup; AB, TA, EGB, ZN, GV, GD, AMM and SHS performed the X-ray experiments; SIB performed the simulations; AB analyzed the experimental data; AB, SIB and WG wrote the manuscript with contributions from all co-authors.

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### Conflict of Interest

The authors declare no conflict of interest.

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