

# Electrostatically Tuning the Photodissociation of the Irgacure 2959 Photoinitiator in the Gas Phase by Cation Binding

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## **Abstract:**

The low-lying electronic states of Irgacure 2959 (Irg), a Norrish-type I photoinitiator, complexed with a single metal cation are investigated in the gas-phase by tracking the photodissociation yield action spectrum as a function of photon energy. Analysis of the band-shifts using quantum chemical calculations (TD-DFT and SCS-CC2) reveals the underlying influence of the charge on the key electronic energy levels. Since the cations ( $\text{H}^+$ ,  $\text{Li}^+$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Zn}^{2+}$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) bind at varying distances, the magnitude of the electric field at centre of the chromophore due to the cation is altered and this shifts the electronic states by different amounts. Photodissociation action spectra of cation-Irg complexes show that absorption transitions to the first  $^1\pi\pi^*$  state are red shifted with a magnitude proportional to the electric field strength (with red shifts  $> 1$  eV) and in most cases the cation is essentially acting as a point-charge. Calculations show that a neighbouring  $^3n\pi^*$  state, a key state the  $\alpha$ -cleavage pathway, is destabilised (blue shifted) by the orientated electric field. As such, if the  $^1\pi\pi^* \rightarrow ^3n\pi^*$  energy gap is reduced, increased inter-system crossing rates are expected resulting in higher yields of the desired radical photoproducts and this is controlled by the orientated electric field arising from the cation.

## **Introduction:**

Controlling chemical reactivity by the application of oriented electric fields (OEFs) is an expanding area of research as both theoretical and experimental investigations reveal new ways of probing and exploiting OEF effects.<sup>1-4</sup> Recent experiments have shown OEFs can enhance ground state reactivity in a variety of contexts including homogenous catalysts in solution,<sup>5</sup> single-molecules at junctions<sup>6</sup> and charged groups interacting with radicals in the gas phase.<sup>7</sup> Recently, Coote and co-workers used computational predictions to rationalise how OEFs can be used to tune the photodissociation properties of radical photoinitiators by shifting the key excited electronic quantum levels implicated in photodissociation.<sup>8-10</sup> This requires the coordinated shifting of the absorption transition with the other states implicated in the dissociation to the desired products.

Following absorption of a photon, it is often the interplay between the spectroscopically prepared excited state and the neighbouring “dark” excited state(s) that mediate the photodissociation efficiency.<sup>8, 10-12</sup> As a result, the photon energy corresponding to the maximum absorption cross-section does not necessarily correspond to the maximum photodissociation efficiency.<sup>12-14</sup> As red-shifting the active wavelengths of photoinitiators is often sought after, since lower energy photons are generally less expensive and are less damaging to other co-located molecules, it is vital that *both* the absorption transition and the other key states shift in accord to maintain high photodissociation yields. Predicting the impact of chemical modification, or application of OEFs, on photoactivity is not straightforward as different excited states have different polarities and polarizabilities and thus respond differently.<sup>8-10</sup> This in turn has complex follow-on effects on intersystem crossing rates, triplet lifetimes and other factors affecting photodissociation. To study these

processes, experiments that probe both excitation and dissociation as a function of photon energy are required and gas-phase photodissociation action spectroscopy—combining laser photodissociation with  $m/z$ -selected ions—is well suited to investigate the fundamental processes of photoinitiator systems.

Gas-phase photodissociation (PD) action spectroscopy provides information on the structural characterisation of ions and this includes the position of metal cations complexed to chromophores<sup>15-21</sup> and the location of protonation sites.<sup>22-30</sup> PD action spectroscopy of ions complements other experimental strategies examining the effect of electric fields on molecular reactivity.<sup>7, 31-37</sup>

This paper focuses on the photodissociation of Irgacure 2959 (Irg), 2-hydroxy-4-(2-hydroxyethoxy)-2-methylpropiophenone, a well-known photoinitiator based on acetophenone with Norrish type-I photo-chemistry<sup>8, 10</sup> and popular for use in bio-printing.<sup>38-40</sup> Irg absorbs in the UV region with an absorption maximum at  $\lambda = 273$  nm.<sup>41</sup> Following absorption, the desired  $\alpha$ -cleavage photodissociation mechanism of Irg is summarised as a  $^1\pi\pi^* \rightarrow ^1n\pi^* \rightarrow ^3\pi\pi^* \rightarrow ^3n\pi^* \rightarrow \alpha$ -cleavage.<sup>8, 10, 11, 42</sup> Because neutral Irg has an  $S_1$  state with  $^1n\pi^*$  character, the  $S_1 (^1n\pi^*) \rightarrow T_n (^3\pi\pi^*)$  ISC pathway—the second step—should be favourable (El Sayed Rules).<sup>43</sup> Ultimately, dissociation from the  $^3n\pi^*$  state correlates to  $\bullet C_9H_9O_3 + \bullet C_3H_6OH$   $\alpha$ -hydroxyalkyl radical.<sup>42</sup> The quantum yield of  $\alpha$ -cleavage from Irg is  $\phi_\alpha = 0.29$  in acetonitrile.<sup>41</sup> Irg has a strong  $\pi \rightarrow \pi^*$  transition ( $\epsilon = 16200$  M<sup>-1</sup> cm<sup>-1</sup> in acetonitrile),<sup>44</sup> which is excited, for example, in the cross linking of hydrogels.<sup>45</sup> Alternatively, to reduce damage in bio-applications, lower energy photons ( $\lambda > 320$  nm) can be used and this directly accesses the weaker  $n \rightarrow \pi^*$  transition ( $\epsilon = 4$  M<sup>-1</sup> cm<sup>-1</sup> for  $\lambda = 365$  nm in ethanol)<sup>38-40, 46</sup> and thus requires longer irradiation times.<sup>45, 47</sup> This trade-off highlights the need to balance the

efficiency of the absorbing transition, which often coincides with higher energy photons, with yields of  $\alpha$ -cleavage and other photo-initiated chemistry.

Hill *et al.* recently outlined that oriented electric fields can be used to (a) decrease the excitation energy of Irg and (b) increase the efficiency of  $\alpha$ -cleavage pathway.<sup>10</sup> Their study targeted that fact that the transition dipoles for the  $^1\pi\pi^*$  and  $^3n\pi^*$  states are anti-aligned (as depicted schematically in Figure 1) and thus are likely perturbed by OEFs in opposite directions. In addition, the  $\pi\pi^*$  states are highly polarizable, which greatly enhances their stabilization ( $>1\text{eV}$ ) in the presence of an appropriately aligned field. Thus, appropriate modification with a charged group or metal cation can lower the  $^1\pi\pi^*$  state to become the  $S_1$  and then, in the absence of any lower lying  $^1n\pi^*$ , the  $S_1 (^1\pi\pi^*) \rightarrow T_n (^3n\pi^*)$  ISC pathway can dominate and enhance  $\alpha$ -cleavage.<sup>8, 10, 11</sup> The efficiency of this pathway will be influenced by the energy gap between the  $^1\pi\pi^*$  and  $^3n\pi^*$  states and a smaller energy gap is expected to increase the ISC rate and increase  $\alpha$ -cleavage yields.<sup>8, 10, 11</sup>

Motivated by these predictions, the present study targets Irg bound to metal cations in the gas phase. Using PD action spectroscopy together with mass spectrometry allows for investigation of the energy shift of the  $^1\pi\pi^*$  states of Irgacure in the presence of different cations ( $M^{Q+}$ ) along with detection of the photoproduct ions. It is observed that the energies of the electronic quantum states are shifted by the presence of the  $M^{Q+}$  ions which altered the (a) the absorption profile and (b) subsequent photodissociation.

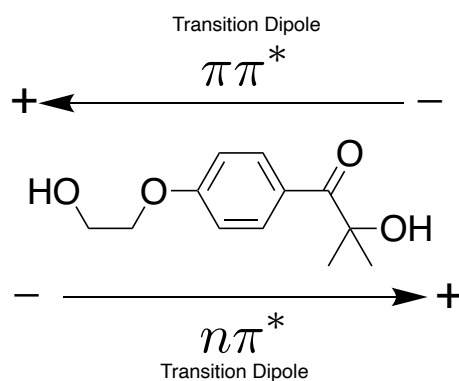


Figure 1. Alignment of transition dipoles for the  $n\pi^*$  and  $\pi\pi^*$  transitions for Irgacure as described by Hill *et al.*<sup>10</sup>

### **Experimental:**

#### **Materials:**

Irgacure 2959 (Sigma Aldrich 98%) was dissolved in HPLC grade methanol to a concentration of  $\sim 1 \mu\text{M}$ . Either Lithium hydroxide, formic acid, potassium chloride, magnesium perchlorate, zinc acetate dihydrate and calcium carbonate were dissolved in HPLC methanol and Milli-Q water and added to separate Irgacure 2959 solutions with a final concentration of  $\sim 100 \mu\text{M}$ .

#### **Photodissociation Action Spectroscopy:**

The methods used for photodissociation action spectroscopy are described in detail elsewhere.<sup>22, 48</sup> Following Julian and co-workers,<sup>49</sup> a commercial, linear quadrupole ion trap mass spectrometer (Thermo Fisher Scientific LTQ VELOS) has been coupled with a tuneable Nd:YAG optical parametric oscillator laser (EKSPLA). Following electrospray ionisation (ESI), populations of either one Irg molecule bound to a single metal mono-cation ( $\text{Irg-M}^{\text{Q}+}$ ) or two Irg molecules bound to a single metal di-cation ( $\text{Irg-M}^{\text{Q}+}\text{-Irg}$ ) were isolated and stored in the ion trap and then irradiated by a single laser pulse, which is directed through the long axis of the ion trap *via* a quartz window mounted at the rear of the mass spectrometer

chamber.<sup>48</sup> This experimental arrangement results in good spatial overlap between the trapped ions and the laser pulse.<sup>50</sup> Approximately 50 ms after the laser pulse, ions are scanned out of the ion trap to record a mass spectrum. These product mass spectra are recorded for a wavelength range spanning between 450 - 250 nm at a step size of either 2 nm for  $\text{Li}^+$ ,  $\text{K}^+$ ,  $\text{Zn}^{2+}$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , or a step size of 1 nm for  $\text{H}^+$  and  $\text{Na}^+$ . At each laser wavelength, *ca.* 150 mass spectra are recorded and averaged, each mass spectrum corresponding to photodissociation of  $\text{Irg-M}^+$  or  $\text{Irg-M}^{2+}\text{-Irg}$  ions by a single laser pulse. The photoproduct yield is then normalised to total ion count as well as laser power as measured with a power meter (STANDA 10MVAA) placed in the beam path following each scan. Mass spectra were recorded with a low  $m/z$  threshold of between 60  $m/z$  and 75  $m/z$  depending on the precursor ion (see Table S1, Supporting Information). Photodissociation action spectra are plotted as the sum of all photoproduct ion signal, normalised to total ion count and laser power.

The yield of  $\alpha$ -cleavage photoproducts relative to depletion of the total photoproduct signal was calculated by dividing the ion count of the  $\alpha$ -cleavage product signal by the total ion count of all photodissociation products. The yield of  $\alpha$ -cleavage relative to depletion of the precursor ion was calculated by dividing the ion count of the  $\alpha$ -cleavage product ions by the difference in “laser-on” and “laser-off” precursor ion intensity (300 mass spectra laser-on and 300 mass spectra laser-off).

### **Computational Details:**

All calculations are relevant to gas phase systems. All density functional theory (DFT) and time dependant-density functional theory (TD-DFT) calculations were performed with the Gaussian16 program package,<sup>51</sup> employing the M06-2X method.<sup>52</sup> For DFT optimisations,

the def2-TZVP basis set was used for Irg-M<sup>+</sup> complexes and the def2-SVP basis set was utilised for the larger Irg-M<sup>2+</sup>-Irg complexes.<sup>53, 54</sup> At least seven isomers of each Irg-M<sup>Q+</sup> ion were optimised using M06-2X. For the lowest-energy gas-phase structures, TD-DFT excitation energies were calculated in Gaussian16. All TD-DFT vertical excitation energy calculations for both Irg-M<sup>+</sup> and Irg-M<sup>2+</sup>-Irg complexes employed the def2-TZVP basis set.

Using the most stable structures—as calculated using M06-2X—the distance between the M<sup>Q+</sup> cation and the centre of mass (COM) of the (taken as the centre of mass of the seven aromatic carbons, the ether oxygen and the ketone oxygen) was determined. These structures were also used to calculate TD-DFT vertical excitation energies with the M<sup>Q+</sup> atom replaced with a point charge P<sup>Q+</sup>.<sup>55, 56</sup> The M06-2X geometry of neutral Irg was used to calculate TD-DFT vertical transition energies in the presence of a static electric field oriented along the long axis of the Irg molecule (see Supporting Information, Figure S1).

The lowest energy structure for each of the complexes were re-optimised using SCS-CC2<sup>57, 58</sup> with the resolution of the identity approximation<sup>59</sup> and using these geometries, SCS-CC2 excitation energies were computed using the TURBOMOLE (V7.2) program package.<sup>60</sup> Irg-M<sup>Q+</sup> calculations with SCS-CC2 made use of the def2-TZVP basis set while the def2-SVP basis set was used for calculations of Irg-M<sup>Q+</sup>-Irg ions.

## **Results and Discussion:**

### **Structures:**

In order to characterise the effect of oriented electric fields (OEFs) arising from the presence of M<sup>Q+</sup> charged atoms on the electronic quantum states of Irg, it is first necessary to determine the preferred location of the charged atom. Figure 2 shows structure of M<sup>+</sup> (M<sup>+</sup> =

H<sup>+</sup>, Li<sup>+</sup>, Na<sup>+</sup>, K<sup>+</sup>) ions complexed with one Irgacure 2959 molecule, which are labelled Irg-M<sup>Q+</sup> in general. Based on the *m/z* values of the ions, the M<sup>2+</sup> metals gave rise to complexes comprising two Irg molecules clustered one M<sup>2+</sup>, with essentially no reproducible signal detected for single Irg-M<sup>2+</sup> clusters. Figure 2 also shows structures for M<sup>2+</sup> = Zn<sup>2+</sup>, Mg<sup>2+</sup>, Ca<sup>2+</sup> and these are labelled as Irg-M<sup>Q+</sup>-Irg. The relative energies of other calculated Irg-M<sup>Q+</sup> structures are shown in Figure S2 in Supporting Information. In all cases, Structure A (M<sup>Q+</sup> binding to the ketone and hydroxide oxygens), as shown in Figure 2, is the lowest energy structure.

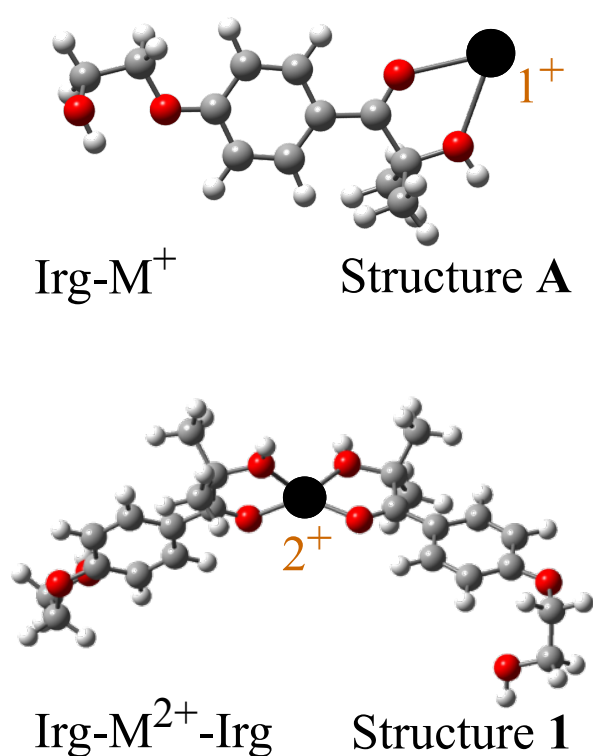


Figure 2: Lowest energy structures for Irg-M<sup>+</sup> and Irg-M<sup>2+</sup>-Irg complexes as calculated using M06-2X.

It is known that thermodynamically less-favoured gas-phase structures can survive ESI since they are kinetically trapped.<sup>61-65</sup> However it is determined that structures other than the minimum-energy structure **A** can be excluded from the ensuing analysis based on DFT energies and based on their predicted electronic spectra residing above the 3.0 eV to 5.0 eV range. Also, structures could be excluded based on low isomerisation barriers to form Structure **A**. For additional details relating to the structure assignment see Supporting Information Section SI.2.

The lowest energy structure of Irg-M<sup>2+</sup>-Irg (labelled Structure **1**) has the hydroxy and ketone oxygens bound to the M<sup>Q+</sup> ion. This Irg-M<sup>2+</sup>-Irg structure has some underlying C<sub>2</sub>-like symmetry for the chromophore but not for the flexible hydroxyethane tails. Based on the relative energies of Irg-M<sup>2+</sup>-Irg structures as calculated with M06-2X (Figure S5 of Supporting Information), the following analysis assumes the results are related to Structure **1**.

### Action Spectroscopy

Figure 3 contains the photodissociation spectra (black line) of Irg-M<sup>+</sup> and Irg-M<sup>2+</sup>-Irg ions alongside SCS-CC2 calculated vertical transitions below 5.0 eV (green bars). The PD action spectra are plotted as the sum of all photoproduct intensities. Representative product mass spectra are shown Figure S6 of the Supporting Information. The Na<sup>+</sup> and K<sup>+</sup> complexes form  $\alpha$ -cleavage pathway products as a dominant photoproduct pathway, the Li<sup>+</sup> system shows small amounts and the H<sup>+</sup> and the M<sup>2+</sup> cases exhibit a range of photoproducts.

The lowest energy peaks in experimental action spectra are fitted with a Gaussian function (blue line in Figure 3), which is used to assign the position of maximum PD efficiency. Additional Gaussian functions are fitted to include the higher energy peaks and are shown in

Figure S7 of Supporting Information. The centre of this blue Gaussian fit (labelled  $E_{\text{exp}}$ ) will be used and compared with calculated vertical transition energies, although it is worth noting that experimental assignment of the vertical transition energy is subjective.<sup>22, 66, 67</sup>

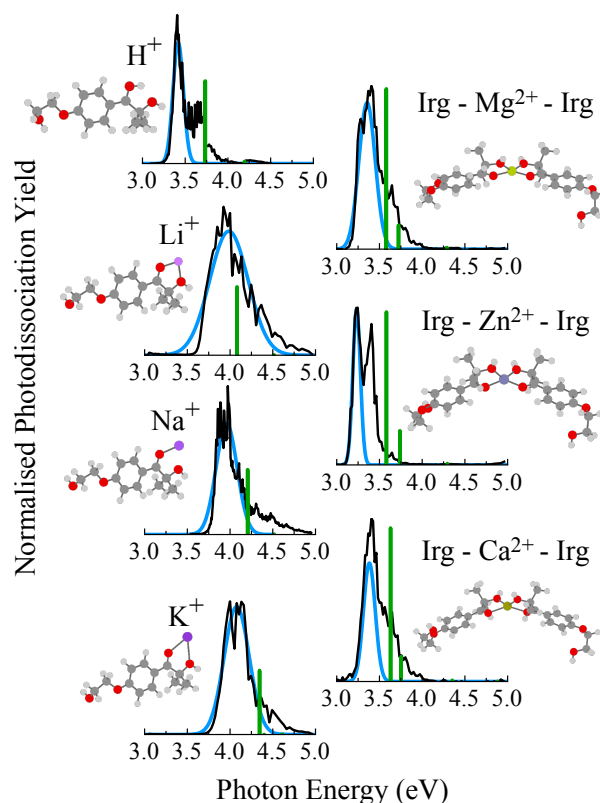


Figure 3: Photodissociation action spectra of Irgacure 2959  $M^{Q+}$  complexes ( $M^{Q+} = H^+, Li^+, Na^+, K^+, Mg^{2+}, Zn^{2+}, Ca^{2+}$ ). Single Gaussian functions (blue) are fit to the lowest energy transition. Additional Gaussian functions used for fitting are shown in Figure S7 of Supporting Information. Green sticks are the calculated vertical transition energies ( $E_{\text{vert}}$ ) for each lowest energy structure using SCS-CC2 with bar heights equal to the oscillator strengths for each respective transition.

The  $E_{\text{exp}}$  values are listed in Table 1 along with TD-DFT and SCS-CC2 vertical transition energies ( $E_{\text{vert}}$ ) for Structure **A** of Irg- $M^+$  and Structure **1** of Irg- $M^{2+}$ -Irg. The  $E_{\text{vert}}$  values calculated using SCS-CC2 and TD-DFT generally agree with  $E_{\text{exp}}$  but, assuming the peak maximum corresponds to the vertical transition energy, with a systematic overestimation of *ca.* 0.3 eV for SCS-CC2 and *ca.* 0.5 eV for TD-DFT, which is consistent with other reports using these methods.<sup>22, 26, 66, 68</sup> Two features are observed for Irg- $M^{Q+}$ -Irg complexes in the

PD action spectra and these are predicted by the SCS-CC2 calculations. Using these calculations, the experimental PD spectra are assigned to the  $\pi \rightarrow \pi^*$  transitions of either Structure **A** for Irg- $M^{Q+}$  or Structure **1** for Irg- $M^{Q+}$ -Irg, for each cation.

Table 1: Centre ( $E_{\text{exp}}$ ) and half width half maximum (HWHM) of Gaussian fit to experimental data. Vertical excitation ( $E_{\text{vert}}$ ) energies and oscillator strengths ( $f$ ) to the first  $^1\pi\pi^*$  state for each ion as calculated using SCS-CC2 and TD-DFT. DNC denotes that the TD-DFT calculation did not converge. <sup>a</sup>SCS-CC2 calculations employed the def2-TZVP basis set for Irg- $M^+$  ions and the def2-SVP basis set for Irg- $M^{2+}$ -Irg ions.

| Ion                 | $E_{\text{exp}}$<br>(eV) | Exp.<br>HWHM<br>(eV) | $E_{\text{vert}}$<br>SCS-CC2 <sup>a</sup><br>(eV) | Oscillator<br>Strength<br>SCS-CC2<br>( $f$ ) | $E_{\text{vert}}$<br>TD-DFT<br>(eV) | Oscillator<br>Strength<br>TD-DFT<br>( $f$ ) |
|---------------------|--------------------------|----------------------|---------------------------------------------------|----------------------------------------------|-------------------------------------|---------------------------------------------|
| Irg- $H^+$          | 3.42                     | 0.07                 | 3.73                                              | 0.76                                         | 4.11                                | 0.66                                        |
| Irg- $Li^+$         | 3.97                     | 0.24                 | 4.08                                              | 0.63                                         | 4.36                                | 0.56                                        |
| Irg- $Na^+$         | 3.96                     | 0.14                 | 4.21                                              | 0.60                                         | 4.47                                | 0.53                                        |
| Irg- $K^+$          | 4.08                     | 0.17                 | 4.35                                              | 0.59                                         | 4.55                                | 0.52                                        |
| Irg- $Mg^{2+}$ -Irg | 3.36                     | 0.11                 | 3.58                                              | 1.52                                         | 3.90                                | 1.34                                        |
| Irg- $Zn^{2+}$ -Irg | 3.23                     | 0.05                 | 3.58                                              | 1.45                                         | 3.86                                | 1.24                                        |
| Irg- $Ca^{2+}$ -Irg | 3.38                     | 0.08                 | 3.63                                              | 1.46                                         | DNC                                 | DNC                                         |

### Shifting of $^1\pi\pi^*$ States by $M^+$ and $M^{2+}$ cations.

Neutral Irg has an  $S_1$  state with  $^1n\pi^*$  character and an  $S_2$  state with  $^1\pi\pi^*$  character. Figure 4 shows the dominant contributing orbitals to these  $S_1$  and  $S_2$  transitions. The highest occupied  $\pi$  and lowest unoccupied  $\pi^*$  orbitals are primarily localised across the phenyl ring ( $C_{1-6}$ ) in addition to on the ether oxygen and the ketone  $C_7O_1$  groups (for atom labelling see Figure S8(A)) and these groups comprise the chromophore of Irg. The  $^1\pi\pi^*$  transition shown in Figure 4 involves a redistribution of the electron density around aromatic ring as well as an

increase around the ketone moiety. In contrast, the  $^1n\pi^*$  transition shifts electron density from the C=O lone pair into the broader  $\pi$  system. The important result of this is that the corresponding transition dipoles for these states are oppositely aligned, as shown in Figure 1.

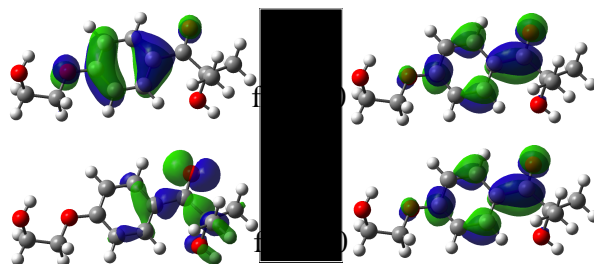


Figure 4: Dominant orbital transitions for the first  $\pi \rightarrow \pi^*$  transition and  $n \rightarrow \pi^*$  transition of neutral Irgacure 2959 (M06-2X/def2-TZVP) with predicted oscillator strengths (f).

As described by other groups, the transition-dipole axis can be thought of as a reaction-axis for OEF control over chemical reactivity.<sup>1-3</sup> As such, if an electric field was oriented from a positive point-charge at the position as  $M^{Q+}$ , near the ketone and OH groups as shown in both cases in Figure 2, then the electric field arising from the cation will stabilise (red-shift) the  $^1\pi\pi^*$  state and destabilise (blue-shift) the  $^1n\pi^*$  state. That is, the field from the cation works with the  $\pi \rightarrow \pi^*$  transition but works against the  $n \rightarrow \pi^*$  transition.<sup>8, 10, 11</sup> Ultimately, the stabilization of the  $\pi\pi^*$  state is in large part due to its polarizability, which leads to significant stabilization despite its almost negligible dipole in the absence of the cation.<sup>8, 10, 11</sup>

Experimentally, it is known that the absorption maximum of neutral Irg in acetonitrile is  $\lambda_{\max} = 273$  nm (4.54 eV),<sup>41, 42</sup> which corresponds to the  $\pi \rightarrow \pi^*$  transition. Since the gas-phase  $\lambda_{\max}$  for neutral Irg is not reported, so in the absence of this value the experimental red shifts (Figure 3) are reported here as shifts relative to this reported acetonitrile  $\lambda_{\max}$  value. The experimental shifts, assigned as transitions to the  $^1\pi\pi^*$  state of each system, are listed in

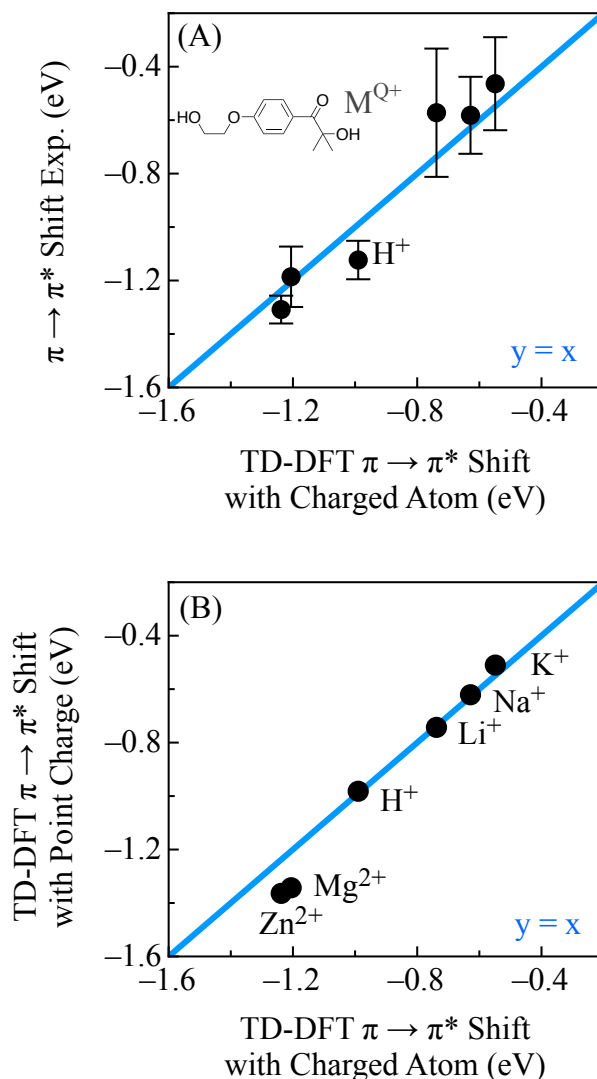
Table 2 along with the TD-DFT calculated shift. Figure S8 shows the distances between the centre of mass (COM) of the chromophore and the charged atom and are listed in Table 2. From the results, the mono-cations give rise to red shifts up to 1.18 eV measured for Irg-H<sup>+</sup>. It is apparent that as the effective radius of mono-cationic M<sup>+</sup> atom increases, its binding distance from the chromophore increases (see Figure S8A and Table 2). For the di-cationic Irg-M<sup>2+</sup>-Irg systems shifts are over 1 eV, relative to neutral Irg are measured. Shifting of electronic<sup>18, 19</sup> and vibrational<sup>69</sup> transitions due to bound M<sup>Q+</sup> cations has been reported in gas-phase action spectra by other groups. Electrostatic shifts of electronic states have also been induced using metal chlorides in solution.<sup>11</sup> Overall, the Irg-M<sup>Q+</sup> action spectra reveal that the amount of red-shift for the <sup>1</sup>ππ\* transition increases as the charge increases from +1 to +2. Also, the trend is for the red-shift to increase as the M<sup>Q+</sup> positions closer to the chromophore.

Figure 5A shows a plot of the experimental red shift for the transition to the <sup>1</sup>ππ\* state compared to the calculated TD-DFT red-shift, where there is a good correlation. These calculations thus provide good predictions for the shift of the absorption transitions. To assess if the M<sup>Q+</sup> cations are acting effectively as point charges—and hence if the underlying cause of the shift is primarily electrostatic<sup>32</sup>—TD DFT excitation energies were recalculated with the geometry fixed but with M<sup>Q+</sup> atoms replaced with point charges P<sup>Q+</sup> (Q = +1e or Q = +2e). Figure 5B shows the calculated π → π\* shifts plotted against the shifts calculated for point charges. The mono-cationic shifts are nearly identically to P<sup>1+</sup> point charge values. The di-cationic systems, on the other hand, have a reduced red shift compared to the P<sup>2+</sup> point-

charge values—falling off the linear trend. This may be due to some bonding interaction between the cation and the Irg molecules, thus reducing the effective charge of the  $M^{2+}$  cation. For the Irg- $M^+$  clusters, the correlation between the shift and the point charge values with the  $M^{Q+}$  cations supports the notion that the shifts are an electrostatic effect.<sup>32</sup>

Table 2: Calculated distances between chromophore centre of mass (COM) and charged atom, electric field strength (V/M) calculated using Coulomb's law, transition energy ( $E_{\text{exp}}$ ) shift determined from the PD action spectrum, TD-DFT vertical transition energy shifts ( $E_{\text{vert}}$ ) and  $E_{\text{vert}}$  calculated by replacing  $M^{Q+}$  with a point charge.

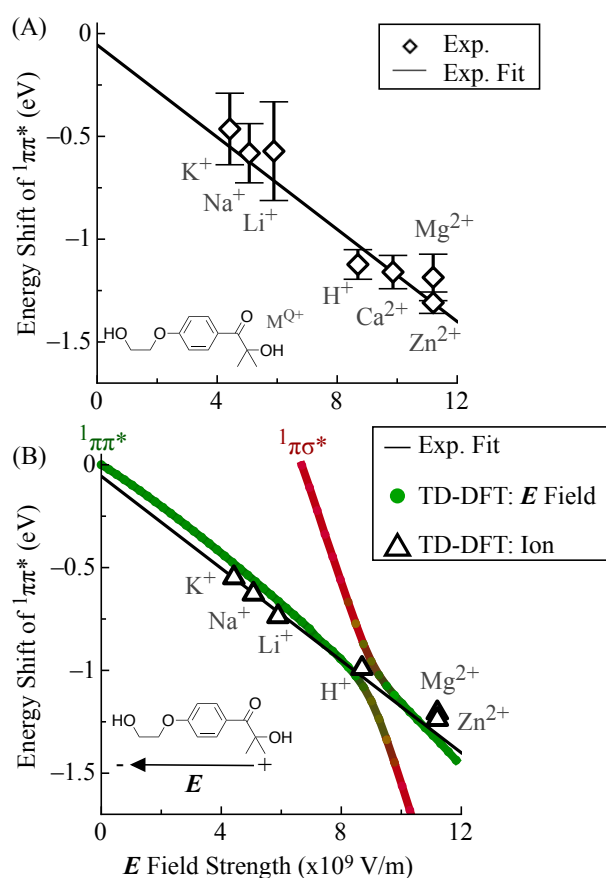
| Ion                 | Cation-Irg Distance (Å) | Electric Field Strength (V/m) $\times 10^9$ | $E_{\text{exp}}$ Shift | $E_{\text{vert}}$ Shift of Ion (TD-DFT) | $E_{\text{vert}}$ Shift with Point Charge (TD-DFT) |
|---------------------|-------------------------|---------------------------------------------|------------------------|-----------------------------------------|----------------------------------------------------|
| Irg- $H^+$          | 4.07                    | 8.69                                        | -1.12                  | -0.990                                  | -0.982                                             |
| Irg- $Li^+$         | 4.95                    | 5.89                                        | -0.57                  | -0.738                                  | -0.743                                             |
| Irg- $Na^+$         | 5.33                    | 5.07                                        | -0.58                  | -0.629                                  | -0.621                                             |
| Irg- $K^+$          | 5.71                    | 4.42                                        | -0.46                  | -0.549                                  | -0.510                                             |
| Irg- $Mg^{2+}$ -Irg | 5.07                    | 11.2                                        | -1.19                  | -1.206                                  | -1.343                                             |
| Irg- $Zn^{2+}$ -Irg | 5.07                    | 11.2                                        | -1.31                  | -1.238                                  | -1.364                                             |
| Irg- $Ca^{2+}$ -Irg | 5.41                    | 9.86                                        | -1.16                  | DNC                                     | -1.336                                             |



**Figure 5:** Plot of  $\pi \rightarrow \pi^*$  transition of Irg- $M^{Q+}$  shift relative to neutral Irg calculated by TD-DFT versus (A) the experimental value from the photodissociation action spectra and (B) the shift as modelled by a point charge.

To further explore the underlying cause of the band shift—and the influence of the metal cation—the electric field strength ( $E$ ) is calculated using Coulomb’s law<sup>43</sup> (as described in Section SI.6 of Supporting Information). We note that this is a somewhat simplified approximation of the electric field strength, as it is simply the value of the electric field strength at a single distance to a point on the Irg chromophore and the charge  $Q_M$  (either  $+1e$  or  $+2e$ ). Values for each system are shown in Table 2. Figure 6A shows the plot of the

experimental redshift ( $E_{\text{exp}}$  shift) of the  $\pi \rightarrow \pi^*$  transition for each ion complex (relative to neutral Irg) against the electric field strength ( $E$ ) calculated to arise from  $M^{Q+}$  (with error bars from the HWHM from the experimental band, *vide supra*). A fitted linear function (black line), shows that the experimental band shift of the transition correlates with the electric field strength at the chromophore COM ( $R^2 = 0.95$  and y-intercept of  $-0.06 \pm 0.3$  eV). Importantly, the fit passes through origin in accord with 0 V/m electric field affecting zero red shift. In this case of Irg- $M^{Q+}$  ions, and for other Norrish type-I photoinitiators,<sup>8, 10</sup> the charge-induced dipole alignment – moderated by the polarizability – provides a clear rationalisation of the excited-state energy shift.



**Figure 6:** Energy shift of the transition to the first  $1\pi\pi^*$  state for Irg- $M^{Q+}$  as a function of the electric field strength  $E$ . (A) Diamonds are the experimental peak position, error bars are the  $\pm$ HWHM of the fitted Gaussian. Black line is a linear regression fit to experimental data. (B)

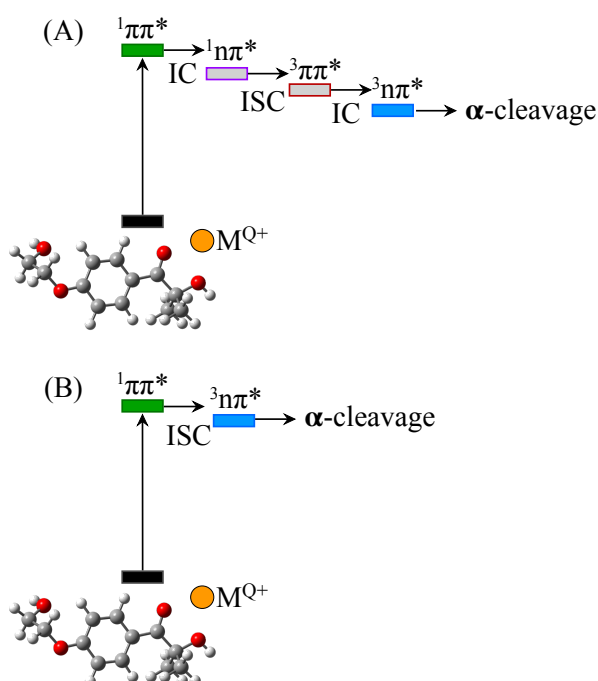
Triangles are the vertical excitation energies of the transition to the  $^1\pi\pi^*$  state (M06-2X/def2-TZVP). The green trace is the  $^1\pi\pi^*$  transition energy (M06-2X/def2-TZVP) under static electric fields of different strengths and the red trace follows a  $^1\pi\sigma^*$  state which interacts with the  $^1\pi\pi^*$  state at higher  $E$  values (see text).

For the calculations, the vertical excitation energies to the  $^1\pi\pi^*$  state of Irg- $M^+$  and Irg- $M^{2+}$ -Irg ions relative to neutral Irg values are plotted in Figure 6B (triangles). The green trace is the vertical  $^1\pi\pi^*$  excitation energy for neutral Irg in the presence of an increasing static electric field (oriented along the axis of neutral Irg as shown in Figure S1 of Supporting Information). It was found that at higher electric field values, the  $^1\pi\pi^*$  state of interest interacted with a higher lying  $^1\pi\sigma^*$  state (shown as red trace) and this state is dramatically stabilised by the electric field. Although these states interact well-above the  $E$  field values for the mono cations, they become mixed around  $9 \times 10^9$  V/m and invert at electric field strengths above  $10 \times 10^9$  V/m (These  $^1\pi\pi^*$  and  $^1\pi\sigma^*$  orbitals are shown in Figure S9 of Supporting Information). State-mixing and orbital-mixing is a common feature of molecular species in OEFs.<sup>3</sup> It is not suspected that the  $^1\pi\sigma^*$  state is involved in the dissociation of the high-field (or any) complexes here. As mentioned above the dissociation products for the Irg- $Na^+$  and Irg- $K^+$  complexes cleanly photodissociate to  $\alpha$ -cleavage pathway products, Irg- $Li^+$  does in small yields, but the Irg- $H^+$  complex and the Irg- $M^{2+}$ -Irg systems do not. The  $\alpha$ -pathway mechanisms are discussed in the next section.

## Photodissociation Pathways

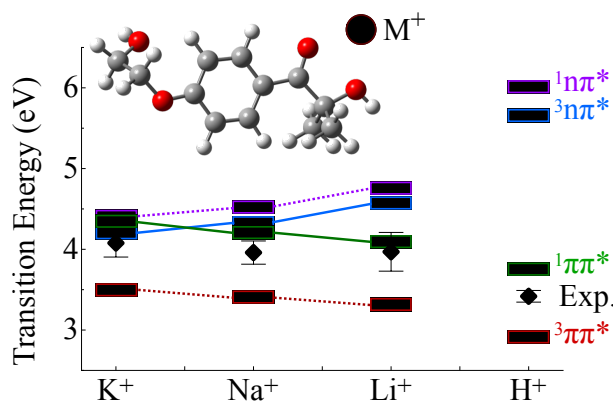
We have shown that the proximity of the cation affects the amount of red-shift for the key absorbing transition to the  $^1\pi\pi^*$  state of Irg- $M^{Q+}$  ions. This achieves the goal of decreasing the photon energy required for excitation. The next required step is efficient formation of

radical products *via*  $\alpha$ -cleavage. Two pathways resulting in  $\alpha$ -cleavage are shown in Figure 7, these are canonical acetophenone-type pathway<sup>8, 10</sup> (Figure 7A) and the more direct ISC pathway (Figure 7B). It is theorised that the efficiency of  $\alpha$ -cleavage is enhanced when the canonical acetophenone-type photo-dissociation pathway ( $^1\pi\pi^* \rightarrow ^1n\pi^* \rightarrow ^3\pi\pi^* \rightarrow ^3n\pi^* \rightarrow \alpha$ -cleavage) is negated by lowering the  $^1\pi\pi^*$  state below the  $^1n\pi^*$  state.<sup>10, 11</sup> Once achieved, the  $S_1$  state is  $^1\pi\pi^*$ , and this opens up the more direct  $^1\pi\pi^* \rightarrow ^3n\pi^* \rightarrow \alpha$ -cleavage pathway.<sup>8, 10, 11</sup> This direct ISC from the  $S_1$  ( $^1\pi\pi^*$ ) to the  $T_n$  ( $^3n\pi^*$ ) state must still compete with radiative decay and other non-radiative decay pathways but overall enhancement of ISC is afforded by the decreasing energy gap between the  $S_1$   $^1\pi\pi^*$  state and the  $T_n$   $^3n\pi^*$  state.<sup>10</sup> Dissociation from  $^3\pi\pi^*$  states is predicted to be slow<sup>11, 70</sup> while ISC to the triplet manifold and  $\alpha$ -cleavage from the  $^3n\pi^*$  state is ultra-fast.<sup>42</sup>



**Figure 7:** Two  $\alpha$ -cleavage pathways where (A) the  $S_1$  state is  $^1n\pi^*$  character and follows a multistep mechanism and the simpler case (B) where the  $S_1$  state is  $^1\pi\pi^*$  character pathway.

Using the framework shown in Figure 7, Figure 8 shows the vertical transition energies to the first  $^1\pi\pi^*$ ,  $^1n\pi^*$ ,  $^3\pi\pi^*$  and  $^3n\pi^*$  states of each Irg- $M^{Q+}$ . The Irg- $M^{Q+}$ -Irg complexes are excluded from this analysis because of their more complex dissociation mass spectra, which presumably arise from other mechanisms. To accurately characterise different spin states, the SCS-CC2 method was used to calculate vertical excitation of these various spin state. CC2 is a robust method for calculating the excitation energies of medium sized molecules and the SCS correction improves results for open shell systems such as the triplet states investigated here.<sup>71</sup> Calculated  $^1\pi\pi^*$  energies (green rectangles in Figure 8) are compared with experimental energies of the first  $^1\pi\pi^*$  state (black diamonds in Figure 8) and agree well. Therefore, SCS-CC2 better reproduces absolute vertical transition energies, whereas TD-DFT performed well for relative energy shifts but consistently overestimated absolute transition energies by  $\sim 0.5$  eV.



**Figure 8:** Vertical transition energies to the first  $^1\pi\pi^*$  state (green rectangles), the first  $^3\pi\pi^*$  state (blue rectangles), the first  $^3\pi\pi^*$  state (red rectangles) and the first  $^3n\pi^*$  state (purple rectangles) calculated using SCS-CC2/def2-TZVP. Values are compared to the lowest energy feature observed in the action spectra (black diamonds).

The encroachment of the  $M^+$  cation to the chromophore (from Irg- $K^+$  to Irg- $H^+$ ) red shifts the transition to the  $\pi\pi^*$  state (green and red rectangles in Figure 8) while raising the transition energy to the  $n\pi^*$  state (blue and purple rectangles in Figure 8). It is worth noting that in the

case of Irg-H<sup>+</sup> the n $\pi^*$  is affected differently because the proton interacts with the n orbital in a way that cannot be described solely by electrostatic effects. For all Irg-M<sup>Q+</sup> ions, the OEF arising from the presence of the cation stabilises the <sup>1</sup> $\pi\pi^*$  such that it shifts *below* the energy of the <sup>1</sup>n $\pi^*$  state thus it favours the ISC pathway from S<sub>1</sub> (<sup>1</sup> $\pi\pi^*$ ) to the T<sub>n</sub> (<sup>3</sup>n $\pi^*$ ) state (in accordance with the El Sayed rules). Because ISC can occur from the <sup>1</sup> $\pi\pi^*$  state to the dissociative <sup>3</sup>n $\pi^*$  state, the more direct <sup>1</sup> $\pi\pi^*$   $\rightarrow$  <sup>3</sup>n $\pi^*$   $\rightarrow$   $\alpha$ -cleavage pathway (Figure 7B) can dominate.

In order to maximise  $\alpha$ -cleavage yield, one can drive ISC to the desired dissociative <sup>3</sup>n $\pi^*$  state by minimising the energy gap between <sup>1</sup> $\pi\pi^*$  and <sup>3</sup>n $\pi^*$  states. This gap is calculated using SCS-CC2/def2-TZVP. The gas-phase PD experiments follow the formation of photoproduct ions and, as such, the PD yield of  $\alpha$ -cleavage product ions can be reported as a fraction of the total product yield and also as a fraction of the total precursor ion depletion.

Table 3 shows the experimental ratio between the  $\alpha$ -cleavage photoproduct ion yield  $\phi_{\alpha\text{-cleavage}}$  and total PD photoproduct yield  $\phi_{\text{products}}$  (or total depletion of the precursor ion  $\phi_{\text{depletion}}$ ) for each Irg-M<sup>Q+</sup> ion plotted against the energy gap between the first <sup>1</sup> $\pi\pi^*$  and <sup>3</sup>n $\pi^*$  states as calculated (SCS-CC2). The Irg-Na<sup>+</sup> and Irg-K<sup>+</sup> ions have the smallest energy gap between the first <sup>1</sup> $\pi\pi^*$  and <sup>3</sup>n $\pi^*$  states and dissociate with a yield of  $\phi_{\alpha\text{-cleavage}} / \phi_{\text{products}} = 0.86$  (Irg-Na<sup>+</sup>) and  $\phi_{\alpha\text{-cleavage}} / \phi_{\text{products}} = 0.97$  (Irg-K<sup>+</sup>). The higher  $\alpha$ -cleavage yield of Irg-K<sup>+</sup> can be rationalised as the <sup>3</sup>n $\pi^*$  being slightly lower in energy than <sup>1</sup> $\pi\pi^*$  state; the corresponding energy difference for Irg-Na<sup>+</sup> value is slightly positive but within the uncertainty of these values. With an unfavourably large energy gap of 0.5 eV, the Irg-Li<sup>+</sup> complex dissociated

with a small yield of  $\phi_{\alpha\text{-cleavage}} / \phi_{\text{products}} = 0.0008$ . Therefore, under low pressure conditions in the gas-phase, other dissociation pathways can dominate for the Irg-Li<sup>+</sup> system.

The ratios of  $\phi_{\alpha\text{-cleavage}} / \phi_{\text{depletion}}$  are lower than for  $\phi_{\alpha\text{-cleavage}} / \phi_{\text{products}}$  because we suspect photoproducts are formed below the  $m/z$  threshold for the experiment. It is quite possible that  $\alpha$ -cleavage resulting in  $\bullet\text{C}_9\text{H}_9\text{O}_3 + \bullet\text{C}_3\text{H}_6\text{OH} + \text{M}^{\text{Q}+}$  is occurring and this would go undetected (and not contribute to the  $\phi_{\alpha\text{-cleavage}}$  value). If this channel was taken into account, then the  $\phi_{\alpha\text{-cleavage}} / \phi_{\text{depletion}}$  ratio would be expected to more closely match the  $\phi_{\alpha\text{-cleavage}} / \phi_{\text{products}}$  value. Nevertheless, the  $\phi_{\alpha\text{-cleavage}} / \phi_{\text{depletion}}$  values follow a similar trend to the  $\phi_{\alpha\text{-cleavage}} / \phi_{\text{products}}$  values. Irg-K<sup>+</sup> has a yield of  $\phi_{\alpha\text{-cleavage}} / \phi_{\text{depletion}} = 0.36$ , while Irg-Li<sup>+</sup> has a yield of  $\phi_{\alpha\text{-cleavage}} / \phi_{\text{depletion}} = 0.00041$ . By tuning the energy gap between  $^1\pi\pi^*$  and  $^3n\pi^*$  quantum states the photochemistry of Irg is altered. This manifests in a yield of  $\alpha$ -cleavage from Irg-K<sup>+</sup> is  $\sim 10^4$  times larger than for Irg-Li<sup>+</sup>.

Table 3: Energy gap between the (vertical)  $^1\pi\pi^*$  and  $^3n\pi^*$  states as calculated using SCS-CC2/def2-TZVP. Experimental ratio between photo-dissociation leading to  $\alpha$ -cleavage ( $\phi_{\alpha\text{-cleavage}}$ ) and total observed photo-dissociation yield ( $\phi_{\text{products}}$ ). Experimental ratio between photo-dissociation leading to  $\alpha$ -cleavage ( $\phi_{\alpha\text{-cleavage}}$ ) and total observed depletion of the precursor ion yield ( $\phi_{\text{depletion}}$ ).

| Ion                 | SCS-CC2<br>Energy Gap<br>$^3n\pi^* - ^1\pi\pi^*$ | Experimental<br>$\phi_{\alpha\text{-cleavage}} / \phi_{\text{products}}$ | Experimental<br>$\phi_{\alpha\text{-cleavage}} / \phi_{\text{depletion}}$ | PD Wavelength<br>(nm) |
|---------------------|--------------------------------------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------------|-----------------------|
| Irg-K <sup>+</sup>  | -0.15                                            | 0.97                                                                     | 0.36                                                                      | 300                   |
| Irg-Na <sup>+</sup> | 0.11                                             | 0.86                                                                     | 0.0096                                                                    | 296                   |
| Irg-Li <sup>+</sup> | 0.48                                             | 0.0008                                                                   | 0.00041                                                                   | 310                   |

## **Conclusion:**

Using ion trap mass spectrometry,  $M^{Q+}$  cations ( $H^+$ ,  $Li^+$ ,  $Na^+$ ,  $K^+$ ,  $Zn^{2+}$ ,  $Ca^{2+}$ ,  $Mg^{2+}$ ) bound to Irg molecules—either one Irg molecule per  $M^+$  monocationic atom or two Irg molecules per  $M^{2+}$  dicationic atom—resulting in electric fields of varying strengths that were oriented internally for each Irg molecule. Gas-phase UV PD spectroscopy, combined with TD-DFT calculations, showed that the first  $^1\pi\pi^*$  transition was red-shifted proportionally to the strength of the electric field arising from the  $M^{Q+}$  cation. Red shifts of the transitions to the  $^1\pi\pi^*$  state are observed from the UVC to the UVB or UVA region (depending on the charged atom), in accordance with prediction by Hill and Coote (2019) that transition energies can be favourably controlled using OEFs.

Radical photoproduct yields of 97% following  $\alpha$ -cleavage we measured for Irg- $K^+$ , which was the system with the smallest energy gap between the first  $^1\pi\pi^*$  and  $^3n\pi^*$  states (as calculated using SCS-CC2). In contrast, Irg- $Li^+$  ions with a  $^1\pi\pi^*$  and  $^3n\pi^*$  gap of 0.5 eV dissociated with 0.08%  $\alpha$ -cleavage. Therefore, with the tuning the  $^1\pi\pi^* - ^3n\pi^*$  energy gap with OEFs, photodissociation can be drastically altered. This study provides combined experimental and theoretical evidence that oriented electric fields can shift photochemical reactivity by tuning the energies of electronic quantum states to affect absorption profiles and photodissociation pathways.

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