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# Monitoring Vibronic Coherences and Molecular Aromaticity in Photoexcited Cyclooctatetraene with X-ray Probe: A Simulation Study<sup>†</sup>

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Understanding conical intersection (CI) dynamics and subsequent conformational changes is key for exploring and controlling photo-reactions in aromatic molecules. Monitoring of their time-resolved dynamics remains a formidable experimental challenge. In this study, we simulate the photoinduced  $S_3$  to  $S_1$  non-adiabatic dynamics of cyclooctatetraene (COT), involving multiple CIs with relaxation times in good agreement with experiment. We further investigate the possibility to directly probe the CI passages in COT by off-resonant X-ray Raman spectroscopy (TRUECARS) and time-resolved X-ray diffraction (TRXD). We find that these signals sensitively monitor key chemical features during the ultrafast dynamics. First, we distinguish two CIs by TRUECARS signals with their appearances at different Raman shift. Second, we demonstrate that TRXD, where X-ray photons scatter off electron densities, can resolve ultrafast changes in the aromaticity of COT. It can further distinguish between planar and non-planar geometries explored during the dynamics, as e.g. two different tetradical-type CIs. The knowledge gained from these measurements can give unique insight into fundamental chemical properties that dynamically change during non-adiabatic passages.

## 1 Introduction

Aromaticity is a property of cyclic (ring-shaped), typically planar (flat) molecular structures with delocalized  $\pi$  electrons that gives increased stability compared to saturated (non-aromatic) compounds having single bonds or other non-cyclic arrangements with the same set of atoms. Aromaticity plays key roles in chemical reactions (electrophilic aromatic substitution<sup>1</sup>), molecular physics (organic semiconductor<sup>2</sup>, aromatic ring currents<sup>3</sup>), and biochemistry, where amino acids serve as building-blocks of proteins. Thus, monitoring conical intersection (CI) dynamics and conformational changes is key for unravelling and controlling photochemical reactions in aromatic molecules.

Cyclooctatetraene (COT) is a conjugated cyclic  $4n$   $\pi$ -electron

system that has a  $D_{8h}$  planar conjugated aromatic  $\pi$ -network in the lowest excited state but is non-aromatic in higher excited states ( $S_{n>1}$ ) as well as in the ground state, where it has a non-planar boat-like  $D_{2d}$  structure with localized single and double C–C bonds. Thus, COT may serve as a prototypical photoactive unit where photon absorption is employed as a control knob to switch between non-aromatic and aromatic states. Therefore, photorelaxation through CIs induces strong modification of the planarity and electron density, thereby aromaticity, but without ring opening like heterocyclic compounds<sup>4,5</sup>.

Its thermal and photochemical relaxation pathways have drawn significant experimental and theoretical attention<sup>6–8</sup> (Scheme 1). A photon initially excites COT to the optically allowed (bright)  $S_{2/3}$  state (1), followed by ultrafast non-radiative decay to the optically forbidden (dark)  $S_1$  state (2). A non-adiabatic transition to  $S_0$  is controlled by two tetradical-type conical intersections (CI)<sup>8,9</sup>,  $CI_{st}$  (3) and  $CI_b$  (4).  $CI_{st}$  has a typical out-of-plane triangular  $-(CH)_3$  kink of triradical nature similar to other unsaturated hydrocarbons<sup>10,11</sup> leading to a three- or four-membered ring formation (5) and cis  $\rightarrow$  trans isomerization (6)<sup>8</sup>. However, the decay via this channel is suppressed by an energy barrier.  $CI_b$  holds a  $C_{2v}$  symmetry and has two unpaired electrons centered at single carbon atoms and two resonance-stabilized allyl radicals<sup>9</sup>. Thanks to its lower barrier, it acts as the elective radiationless channel leading to the formation of semibul-

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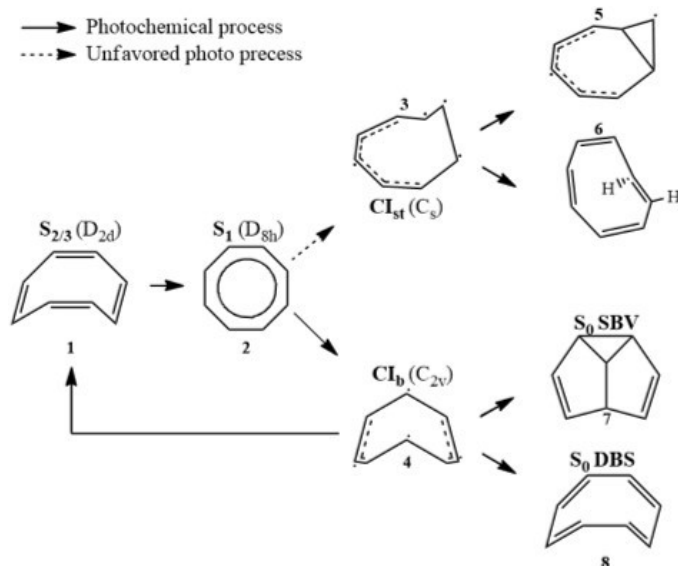
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Scheme 1 Photochemical and thermal reaction scheme for cyclooctatetraene.

valene (SBV, **7**) as a main product<sup>12</sup>, and a double-bond shifted (DBS, **8**) or the original COT (**1**) is formed as byproducts<sup>13</sup>. We refer to ref<sup>8</sup> for the comprehensive photo/thermal reaction pathways.

The DBS yields a degenerate product of the parent COT, where the  $\pi$ -electrons migrate within the octagonal perimeter, resulting in a site exchange between singly- and doubly-bonded carbon atoms eventually leading to photoinduced bond order inversion within the ring. Modulation of these pathways in favor of desired channels could be accomplished by chemical modification with  $\pi$ -donor and -acceptor substituents, or by quantum control strategies, making COT a potent and attractive design unit for e.g. molecular photoswitches that allow a control in aromaticity and bond order<sup>14,15</sup>.

While the  $S_1$  to  $S_0$  relaxation pathway has been extensively studied, the nonradiative  $S_3$  to  $S_1$  decay has remained largely unexplored. It is a key issue prior to unravelling the role of  $S_1/S_0$  CI, since the dark  $S_1$  state is only accessible by relaxation from the higher excited states. The  $S_3 \rightarrow S_1$  relaxation can further affect the nuclear dynamics on  $S_1$ , thus influencing the resulting photoproducts. CIs play important roles in many photophysical and photochemical processes<sup>16,17</sup>. Monitoring CI pathways is important for controlling and achieving desired photoproducts. Various studies have shown that modifying the initial condition of nuclear wavepackets in the electronic states forming the CIs can have tremendous effects on the photoproducts<sup>18,19</sup>, corroborating the necessity of including the  $S_3 \rightarrow S_1$  relaxation mechanism in photoexcited COT.

Thanks to the unique temporal, spectral and spatial resolutions provided by free-electron X-ray light sources, many X-ray techniques have been proposed to monitor the CIs in molecules<sup>20,21</sup>. A popular technique is femto/attosecond spectroscopy, which indirectly probe CIs by depletion/appearance/bifurcation of the absorptive lines<sup>22–24</sup>. Polli et al. have implemented ultrafast opti-

cal spectroscopy to probe light-induced photoisomerization of the rhodopsin and mapped out the energy gap between the ground and excited electronic states as a function of time<sup>25</sup>. Such evidence is indirect and circumstantial and does not give direct signature of CI.

To this aim, Transient Redistribution of Ultrafast Electronic Coherences in Attosecond Raman signals (TRUECARs) has been theoretically proposed<sup>26</sup>. This technique directly monitors vibronic coherences created during the CI passage with no contributions of populations (background-free), which is more direct evidence or which signifies presence of CI better than the energy gap between involved states. In TRUECARs, a hybrid broadband/narrowband pulse used in TRUECARs can offer a good combination of both spectral and temporal resolutions. This stems from the ultrafast timing of CIs as well as the few to tens of eV energy range spanned by the vibronic coherences. It has been theoretically used to monitor the CI passage in photo-relaxation in (4-thio)uracil<sup>27–29</sup> and energy transfer in a heterodimer<sup>30</sup> and a triarylamine trimer<sup>31</sup>. A major difficulty in the implementation of TRUECARs is the precise phase control between two pulses, which is under development. Herein, we focus on how TRUECARs signal distinguishes two different CI passages during the photorelaxation in COT.

On the other hand, time-evolving electronic charge densities at CI passages can be imaged with subfemtosecond resolution using ultrafast time-resolved X-ray diffraction/scattering (TRXD)<sup>32</sup>. In ultrafast TRXD experiments, a molecule is prepared in a time-evolving superposition of states by an optical laser, undergoing non-stationary dynamics, then a hard X-ray probe pulse is scattered by the excited molecule onto a detector, yielding the three components of the scattering signal: elastic scattering, inelastic scattering, and mixed (in)elastic related to electronic coherence contribute to the signal<sup>32,33</sup>. The snapshots at different pump-probe delay creates a movie presenting temporal evolution of electron densities triggered by the pump pulse. Since the pioneering theoretical work of Wilson et al.<sup>32</sup>, there have been an immense development of theory<sup>34–37</sup> to study non-stationary molecular samples in excited electronic states. A novel development of bright XFELs extended the X-ray scattering measurement in solid crystal into gas or liquid phases<sup>38–40</sup>, which involves real-time monitoring of coherent vibrational motion of excited N-methylmorpholine<sup>41</sup> and its orientation of transition dipole moment using gas-phase x-ray scattering<sup>42</sup>. In liquid phase, ultrafast hydrogen bond dynamics<sup>43</sup>, solvent reorganization coupled to intramolecular charge transfer<sup>44</sup>, liquid-liquid phase transition<sup>45</sup>, and structural changes of proteins<sup>46</sup> has been monitored. Nielson et al. have recorded coherent nuclear dynamics with atomistic resolution on the excited<sup>47</sup> and ground state<sup>48</sup> potential energy surfaces for systems in an environment. XFELs is being upgraded to achieve brighter light sources, higher repetition rate, and greater spatiotemporal resolution to expand its applications.

Our previous theoretical work has demonstrated that the TRXD signals can potentially image transient electron transition densities directly associated with CI passages in azobenzene<sup>49,50</sup>, 4-thiouracil<sup>29</sup>, exhibiting characteristic positive/negative oscillations due to the formation of electronic coherences. We further had shown that the two-dimensional diffraction pattern, domi-



nated by elastic scattering, can be used to monitor conformational changes e.g., cis to trans photoisomerization in azobenzene<sup>49</sup>. Such valence electron densities can be used to monitor the electron density (aromaticity) and planarity variation of the molecule.

In the present study, we implement a non-adiabatic excited state molecular dynamics<sup>51</sup> protocol to track the  $S_3 \rightarrow S_1$  relaxation pathway in optically excited COT. We employ a semiempirical ab initio multiple cloning (AIMC) approach based on Multi-Configurational Ehrenfest (MCE), which provides an accurate description of non-adiabatic molecular dynamics in large conjugated molecules<sup>52</sup> with affordable cost.

We capture the appearance of vibronic coherences as well as aromaticity changes upon photorelaxation by ultrafast X-ray probe. The vibronic coherences generated at the multiple CIs are tracked by the TRUECARs signal. We show highly diverse scenarios for excited state relaxation and record the temporal and the energetic profiles of CIs by the TRUECARs signal and its spectrogram. We find that explicit use of transition polarizabilities is crucial to assess accurate observation of vibronic coherences evolving during the CI passage. Due to quantum nature of nuclear motions, the vibronic coherences do not vanish after passing through the CI passage. The TRUECARs signal provides a clear signature of the two CIs ( $S_3/S_2$  vs  $S_2/S_1$ ) by their different timing and energy splitting distributions between the involved states.

We find that TRXD is a powerful tool for the real-time tracking of the aromaticity and molecular conformation changes in molecules by tracking the evolving valence electron densities. The 2D elastic scattering pattern can differentiate the different CI pathways,  $CI_{st}$  and  $CI_b$ , and the photoproduct, SBV from the reactant COT. This helps map the comprehensive relaxation pathways of COT from bright  $S_3$  to  $S_0$  via the dark and aromatic  $S_1$  state.

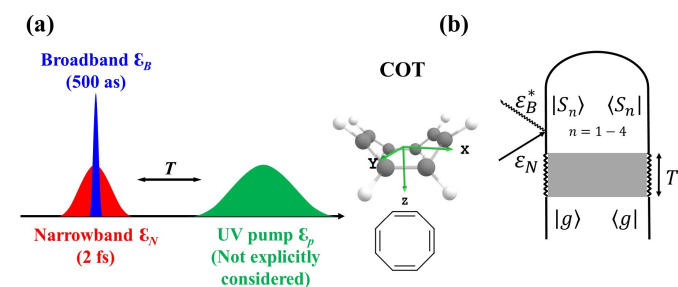


Fig. 1 (a) Pulse configuration and (b) loop diagram for TRUECARs with cyclooctatetraene (COT) placed on the  $xy$  plane (Lewis structure given). The grey area indicates the electronic and nuclear population in the bright  $S_3$  state created by the pump pulse  $\mathcal{E}_p$  (not considered explicitly in the simulation) and a free evolution period of the molecule. At time delay  $T$ , the hybrid  $\mathcal{E}_B$  (broad) and  $\mathcal{E}_N$  (narrow) pulse is applied to probe the dynamics. See ESI for loop diagram rules.

## 2 Results and Discussion

The AIMC approach was employed to describe the  $S_3 \rightarrow S_1$  electronic transitions in COT. AIMC naturally includes decoherence through cloning events when mean-field theory fails to describe two electronic states evolving on very different surfaces.

This approach has been successfully applied to describe photoinduced dynamics in large molecules, such as a dendrimer<sup>31</sup> and a bichromic molecule<sup>30</sup>.

The vibronic coherences emerging at the excited state CIs are tracked by TRUECARs signal and the geometry and aromaticity changes are monitored by the TRXD signal. TRUECARs uses a hybrid field  $\mathcal{E}_N$  (2 fs), with central frequency 200 eV and  $\mathcal{E}_B$  (500 as) following the pump-probe waiting time  $T$  (Fig. 1). The central frequency was chosen to maximize the signal strength by maximizing the polarizability cross section while still staying off-resonant (pre-resonant)<sup>53</sup>. Otherwise the populations will contribute and dominate the coherences<sup>54,55</sup>. The signal is finite only when there is an overlap of nuclear wavepackets in different electronic states, making this technique free from population background. A single broadband pulse with the same central frequency and bandwidth (Fig. S1) is used for TRXD.

We display the TRUECARs/TRXD signal as well as evolution of population, coherence, molecular geometry, averaged over the total 98/57 trajectories with equal weight, in Fig. 2. Note that only the signal averaged over all trajectories is experimentally observable although individual trajectories illustrate different molecular dynamics scenarios. We first note that our AIMC approach well describe the  $S_3 \rightarrow S_1$  photo-relaxation dynamics of COT. The  $S_1$  population dynamics (Fig. 2e) is fitted with  $P(t) = Ae^{-(t-t_0)/k}$ , where with  $t_0 = 26.5$  fs, yielding a 54.5 fs of growth time. This is in a good agreement with our previous surface hopping simulations<sup>56</sup> and time-resolved mass spectroscopy measurement of photoexcited cyclooctatriene and bicyclooctadiene using near-IR photoionization probe<sup>57</sup>, where  ${}^1B_2$  to  ${}^2A_1$  ( $C_{2v}$  symmetry, corresponding to  $S_3$  to  $S_1$  in current study) relaxation was estimated to occur within 67 fs. The average population is distributed with a large fraction (70%) in  $S_1$  and a smaller one in the  $S_2$  (20%) and the others for  $S_3$  to  $S_4$  states at 250 fs.

The TRUECARs signal (Eqn 4 and 5) is visible over the entire simulation time, with stronger magnitudes at e.g. 0 to 70 fs. The two CI passages are well captured by the TRUECARs signal ( $S_2/S_1$  in Fig. 2b and  $S_3/S_2$  in Fig. 2c). The molecule enters the  $S_3/S_2$  CI region, with strong nonadiabatic coupling (NAC) (Fig. 2h) due to their close spacing in energy (Fig. 2d), creating a vibronic coherence (Fig. 2f) and thereby the TRUECARs signal shows up from the beginning and maintain its amplitude until 70 fs (Fig. 2c). A delayed  $S_2/S_1$  CI is observed (Fig. 2b) as the major population transfer occurs between 50 and 100 fs, but the relevant TRUECARs signal remains strong until 170 fs. We note that after the second CI,  $S_2$  and  $S_1$  evolve differently, and their energy splitting increases, as the TRUECARs is observed at higher Raman shift  $\omega_r$  (Fig. 2b). We find that the  $S_4$  state is only slightly affected in all trajectories.

In our previous studies<sup>30,31</sup>, we used a constant polarizability over the nuclear space and all coherence contributed to the TRUECARs signal according to their magnitude with no further selectivity. This approximation holds when only two electronic states are involved, but as soon as more than one electronic transition is involved, the relative transition polarizability strengths determine the magnitude of the individual contributions to the total signal. This means while the coherences themselves could





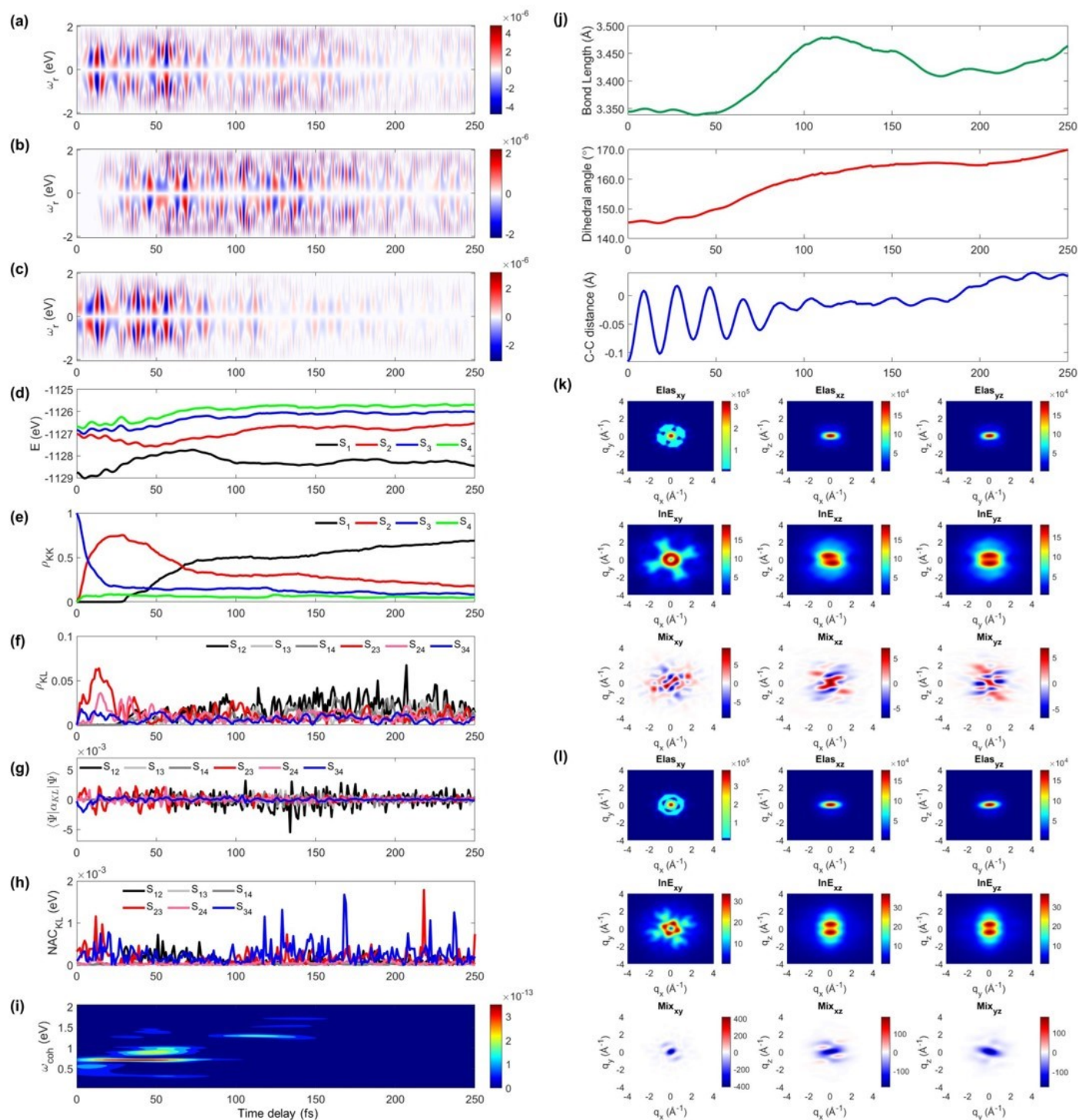


Fig. 2 TRUECARs and TRXD signal and relevant molecular properties in the ensemble of 98/57 trajectories of the COT. The averaged frequency-dispersed TRUECARs signal  $S(\omega_r, T)$ , for (a) Total, (b)  $S_2/S_1$  coherence, (c)  $S_3/S_2$  coherence. (d) Combined potential energy surfaces of the electronic states in all trajectories. (e) Averaged population in the electronic states. (f) Averaged coherence magnitude  $\rho_{KL}$  between electronic states, according to Eqn 3. (g) Averaged expectation value of the polarizability operator calculated with Eqn 5. (h) Averaged nonadiabatic coupling magnitude for each coherence  $\rho_{KL}$ . (i) Averaged FROG spectrogram, according to Eqn 7, which is extracted from the TRUECARs signal by integrating over the negative Raman shifts ( $\omega_r < 0$ ). (j) Time evolution of averaged molecular geometry, bond length (top), dihedral angle ( $C_1-C_4$  in Fig. S6a), and bond alternation (bottom). (k) Averaged Two-dimensional TRXD scattering pattern projected on the  $xy$  (left),  $xz$  (middle), and  $yz$  (right) plane at  $T = 1$  fs. The top, middle, and bottom panel shows contribution from elastic scattering, inelastic scattering, and mixed elastic/inelastic scattering (coherence) to the total signal, respectively. (l) same as (k) but at  $T = 250$  fs

be equally strong, the coherence associated with the higher transition polarizability will dominate the TRUECARS signal. We display the TRUECARS signal calculated with geometry-independent polarizability over the nuclear space in Fig. S2. We find that the signal is particularly strong at 0 to 25 fs for  $S_3/S_2$  and 90 to 100 fs for  $S_2/S_1$ . This signal looks more sensitive to the timing of the CIs, but the relative transition polarizability strengths determine the observed signal shown in Fig. 2a. This is more evident in trajectory 3 (Fig. S3). The total coherence magnitude is maintained between 0 and 60 fs (Fig. S3d), but the TRUECARS signal is strongest between 40 fs and 60 fs (Fig. S3a) due to the large transition polarizability (Fig. S3c). If geometry independent polarizabilities were used, the TRUECARS signal would be equally strong between 0 fs and 60 fs as shown in Fig. S3b. This implies that, for systems undergoing multiple CIs, both the relative strength of the polarizabilities and the topologies of potential energy surfaces influence the signal and need to be properly accounted in the simulations.

The integrated TRUECARS spectrogram reveals the energy splitting distribution between electronic states involved in the coherence<sup>28</sup>. In turn, a transient energy splitting is encoded in the temporal gain/loss oscillations in the TRUECARS signal at a given Raman shift ( $\omega_r$ ). We display the integrated frequency resolved optical-gating (FROG)<sup>58</sup> spectrogram, given by Eqn 7, in Figure 2i. The spectrogram between 0 and 25 fs is distributed between 0.3 and 0.7 eV, representing the energy splitting between  $S_2$  and  $S_{3/4}$  during the first CI passage. The  $S_2/S_1$  CI passage is captured from 30 to 50 fs. It is more evident in Fig. S4a, where the FROG spectrogram reveals the energy splitting of CI at Raman shift  $\omega_r = 0.02$  eV. An increasing energy splitting between  $S_1$  and higher excited state can be observed where the spectrogram evolves from 1 to 2 eV after 50 fs (Fig. S4b and c). The frequency profile of the spectrogram maps the energy gap between the relevant states in Fig. 2d.

The time-evolving geometric features are displayed in Fig. 2j. These include the bond length ( $C_1-C_3$ , top panel), dihedral angle ( $C_1$  to  $C_4$ , middle panel), and bond length alternation ( $0.5*(b_{15}+b_{48})-b_{18}$ , bottom panel) over time (The atomic labels are given in Fig. S6). Earlier, we have used the same parameters to monitor the non-adiabatic passage of COT using semiempirical trajectory surface hopping dynamics<sup>56</sup>. Based on the Franck-Condon approximation, the molecular geometry starts from the non-planar  $S_0$  minimum conformation with different  $C_1-C_5$  versus  $C_4-C_8$  bond length, and then approach to those at planar  $S_1$  minimum geometry with equalized bond length. Indeed, the dihedral angle approaches to  $180^\circ$ , and atomic distance increases to 3.6 Å as the population is transferred to the  $S_1$  state.

Previously, we had demonstrated that the coherence contribution to TRXD signal can image the evolving electron densities during the CI passage, which is characterized by its phase oscillation between gain and loss along the temporal axis<sup>29,49</sup>. The temporal oscillation showed the strongest intensities during the CI passage and the observed phase change corresponds to real-space phase changes of electron density as the molecule crosses the CI. The coherence contribution involves mixed elastic and inelastic scattering events, where the latter involves only a single active elec-

tron transition. Hence it is weak and buried under the stronger state densities, where all electrons contribute to the signal. We had suggested to extract the information by observing at higher momentum transfer<sup>49</sup>, however, it only works for systems where the transition density is more localized in real space (high  $q$ ) than the delocalized state densities (low  $q$ ). The valence excited states in COT, where an electron in occupied  $\pi$  orbital is promoted to an unoccupied  $\pi^*$  orbital, exhibit delocalized electron densities (Fig. S5), thus the hard X-ray are not beneficial in COT. Frequency-resolved diffraction set-up<sup>59</sup>, can be alternatively used since the coherences oscillate faster than the populations. In those studies, we had assumed very short wave (more than 20 keV), which is currently unavailable, and convolutes the temporal resolution, rendering the experiment difficult. Currently, up to 25 keV is being developed using superconducting accelerators at the European X-ray Free Electron Laser in Hamburg and the Stanford Linear Coherent Light Source. A development of the large free electron laser facilities will enable to directly observe the evolving coherence electron densities in the future.

The state densities are virtually identical for ground state and excited state, and sensitive to the molecular conformation and electron densities. Hence, we expect that TRXD can be used to monitor the change in the molecular conformation (non-planar to planar) and aromaticity (localized electron densities at double bond to delocalized densities). We display two-dimensional (2D) TRXD signal in Fig. 2k and 2l. Note that the 2D patterns shown in Fig. 2 to 4 are imaged only with the valence electron densities since the semiempirical AIMC-NEXMD calculations use basis functions composed of only valence electrons. For comparison, we display the 2D pattern of the TRXD signal for  $S_0$  and  $S_1$  optimal geometries in Fig. S7, calculated with CASSCF(8e/8o), involving all  $\pi$  and  $\pi^*$  orbitals at 6-31G\* basis set. The elastic scattering pattern projected on the xy plane shows the localized double bond features in  $S_0$  minimum. In contrast, the pattern exhibits well delocalized electron density over the entire ring in  $S_1$  minimum conformation, as the molecular geometry becomes planar and all valence bonds are equalized. Comparing the 2D pattern projected on the xz and yz pattern is less sensitive but we observe an elongated pattern in the  $S_1$  minimum conformation compared to that of non-planar conformation. We observe that the signal shows similarity with that of  $S_0$  minimum in the beginning (at 1 fs, Fig. 2k) but ends with the pattern (at 250 fs, Fig. 2l) similar to that of  $S_1$  minimum.

The inelastic scattering contribution from electronic populations (middle panels) or mixed elastic/inelastic scattering contribution from electronic coherence (bottom panels) does not exactly match with those in Fig. S7, because they are calculated without considering the population (wave function coefficients) of the adiabatic states. It is not straightforward to directly compare them. Nevertheless, we note that the coherence contribution exists from 1 fs as the molecule enter the  $S_3/S_2$  CI immediately. Their phase oscillation along the temporal axis could be also used to directly monitor the CI passage.

On a side note, we show that TRXD signal can also be used to track the following  $S_1 \rightarrow S_0$  dynamics, owing to the different conformation of two CIs and photoproducts. We adopted their



optimized geometry from the previous study<sup>8</sup> and display their static 2D XRD pattern, projected on the xy plane in Fig. S6. We find that the CI<sub>b</sub> (Fig. S6c) and its main product SBV (Fig. S6e) exhibit sufficiently different XRD patterns compared to the CI<sub>st</sub> (Fig. S6d) and original COT (Fig. S6a). The presented and discussed 2D TRXD signal may be only accessible by simulation, if alignment of COT is not achievable.

Next, we explore two individual trajectories illustrating very different molecular dynamics scenarios. This is only possible in simulations, since only the ensemble averaged signal is observed in experiments. However, exploring individual trajectories do help understand the entire molecular physics. We first describe trajectory 1, a representative scenario, where most (83%) of the populations ends with S<sub>1</sub> within 100 fs without cloning events. A molecule enters the S<sub>3</sub>/S<sub>2</sub> CI region with an immediate population transfer from S<sub>3</sub> to S<sub>2</sub> (Fig. 3e), thus the TRUECARs signal shows up from the beginning (Fig. 3a and 3c). S<sub>3</sub> and S<sub>2</sub> then evolve differently (S<sub>2</sub> approaches to the second CI), their energy splitting increases, and the TRUECARs signal (Fig. 3c) shows faster oscillation at 20 to 30 fs than 10 to 20 fs. The second CI is visited at 30 fs, when the major population transfer between S<sub>2</sub> and S<sub>1</sub> is facilitated (Fig. 3e) by their large NAC (Fig. 3h). Then, the TRUECARs signal frequencies are shifted to larger Raman shifts (Fig. 3b) as the electronic energy gap between the involved states, S<sub>1</sub> vs S<sub>2/3/4</sub>, increases, while S<sub>1</sub> is stabilized. Note that there is no finite population transfer between S<sub>2</sub> and S<sub>1</sub> (after CI), but their coherence (Fig. 3f) is maintained. The signal gets even stronger as the expectation value of the transition polarizability (Fig. 2f) remains strong in this region.

The time-evolving geometric features and the 2D TRXD signal displayed in Fig. 2j to 2l, probes that the molecule ends with planar and aromatic geometry at 83 fs, as the most of the population ends with S<sub>1</sub>. Note that the simulation is terminated at 83 fs due to the fact that the trajectory has reached the region where the energy gap between the S<sub>1</sub> and S<sub>0</sub> is smaller than 0.1 eV (assumed to be S<sub>0</sub>/S<sub>1</sub> CI, see Method section below).

Next, we illustrate an extreme opposite scenario, where several cloning events happen and the non-adiabatic simulation is terminated before reaching to the S<sub>1</sub> minimum (Fig. 4). In this scenario, the S<sub>3</sub> state, which decays immediately in trajectory 1, survives until 110 fs (Fig. 4e). The major population transfer between S<sub>2</sub> and S<sub>3</sub> states occurs at 10 fs, slower than the immediate occurrence in trajectory 1. The corresponding TRUECARs becomes strongest between 20 and 40 fs when the S<sub>2</sub> state is significantly populated and the coherence  $\rho_{23}$  (and thereby the expectation value of transition polarizability) is large (Fig. 4f). After 20 fs, the S<sub>3</sub> and S<sub>2</sub> state evolve differently,  $\rho_{23}$  decreases, and their energy gap increases. Eventually, at 30 fs, mean-field theory breaks down and a cloning event occurs to describe the different evolution of the S<sub>2</sub> and S<sub>3</sub> states separately.

Another cloning event happens at 60 fs, when the major population transfer between the S<sub>2</sub> and S<sub>1</sub> ends (Fig. 4e). Due to the finite energy splitting between them (Fig. 4d) and small NAC (Fig. 4h), the S<sub>1</sub> state is not significantly populated. Hence, the TRUECARs signal augmented by the S<sub>2</sub>/S<sub>1</sub> coherence (Fig. 4b) is an order of magnitude weaker than that from the S<sub>3</sub>/S<sub>2</sub> coher-

ence (Fig. 4c). We find the latter dominates the total signal as the  $\langle \Psi_2(t) | \alpha_{S_2S_3} | \Psi_3(t) \rangle$  transition polarizability is strongest (Fig. 4g). The integrated FROG spectrogram shown in Figure 4i well describes the increasing energy splitting between S<sub>2</sub> and S<sub>3</sub> between 20 and 40 fs, and decreasing pattern thereafter.

We find that the relevant geometric features do not converge to those of S<sub>1</sub> minimum conformation at the end of the dynamics simulation (115 fs) because the majority of the population stays in the S<sub>2</sub> state, which has a boat-like non-planar conformation, similar to S<sub>0</sub> minimum. The dihedral angle is larger than 20° and the bond length is maintained shorter than the delocalized ring. Thus, the 2D elastic scattering pattern projected on xy plane at 115 fs shown in Fig. 4l, maintains the localized double bond feature, when comparing to Fig. 4k at 1 fs.

Examination of all 98 (for TRUECARs) or 57 (for TRXD) trajectories shows highly diverse scenarios. The two trajectories discussed above are exemplary cases that contribute to the total ensemble. The consequences of the other non-adiabatic dynamics trajectories are placed in between the above-mentioned typical cases. Overall, we demonstrated that AIMC dynamics successfully describes the ultrafast S<sub>3</sub> to S<sub>1</sub> relaxation of excited states, despite the diverse evolution of individual trajectories. Note again, that only ensemble averaged signal can be observed in experiments.

The implementation of the proposed TRUECARs and TRXD experiments requires precise phase control between narrow and broad pulses, and the alignment of COT molecules perpendicular to the propagation of the X-ray probe pulse, respectively. Extracting coherence information in TRXD signal requires very hard X-ray beam, which is under development. Once achieved, the timing of the CI passages and the energetic nature of vibronic coherences can be captured by the TRUECARs spectrogram at different Raman shifts. The evolving electron densities and molecular conformation could be tracked by TRXD signals. The signal is off-resonant with any molecular transition; it does not require any specific core property, and directly reveals the coherences between valence electronic states.

### 3 Conclusions

We have carried out an AIMC molecular dynamics simulation to study non-adiabatic dynamics of photoexcited cyclooctatetraene, tracing its internal conversion from the bright S<sub>3</sub> to the dark S<sub>1</sub> state. The resulting excited state lifetime shows an excellent agreement with experiment, demonstrating an adequate characterization of the molecular photophysics by the semi-empirical multi-configurational Ehrenfest approach. The vibronic coherences created at the two major CI passages persist across ensemble averaging over 98 trajectories and are well captured by TRUECARs signal at different Raman shifts. We demonstrated that TRUECARs and TRXD in combination can distinguish between different CIs explored during the photoinduced dynamics. Changes in the molecular aromaticity, as well as non-planar to planar geometrical dynamics, are directly resolved in the signals. The signals combined with a semiempirical nonadiabatic molecular dynamics protocol thereby provide an accurate temporal, structural and energetic profiles of the CI pathway, that could reveal novel chemical design opportunities and control knobs for





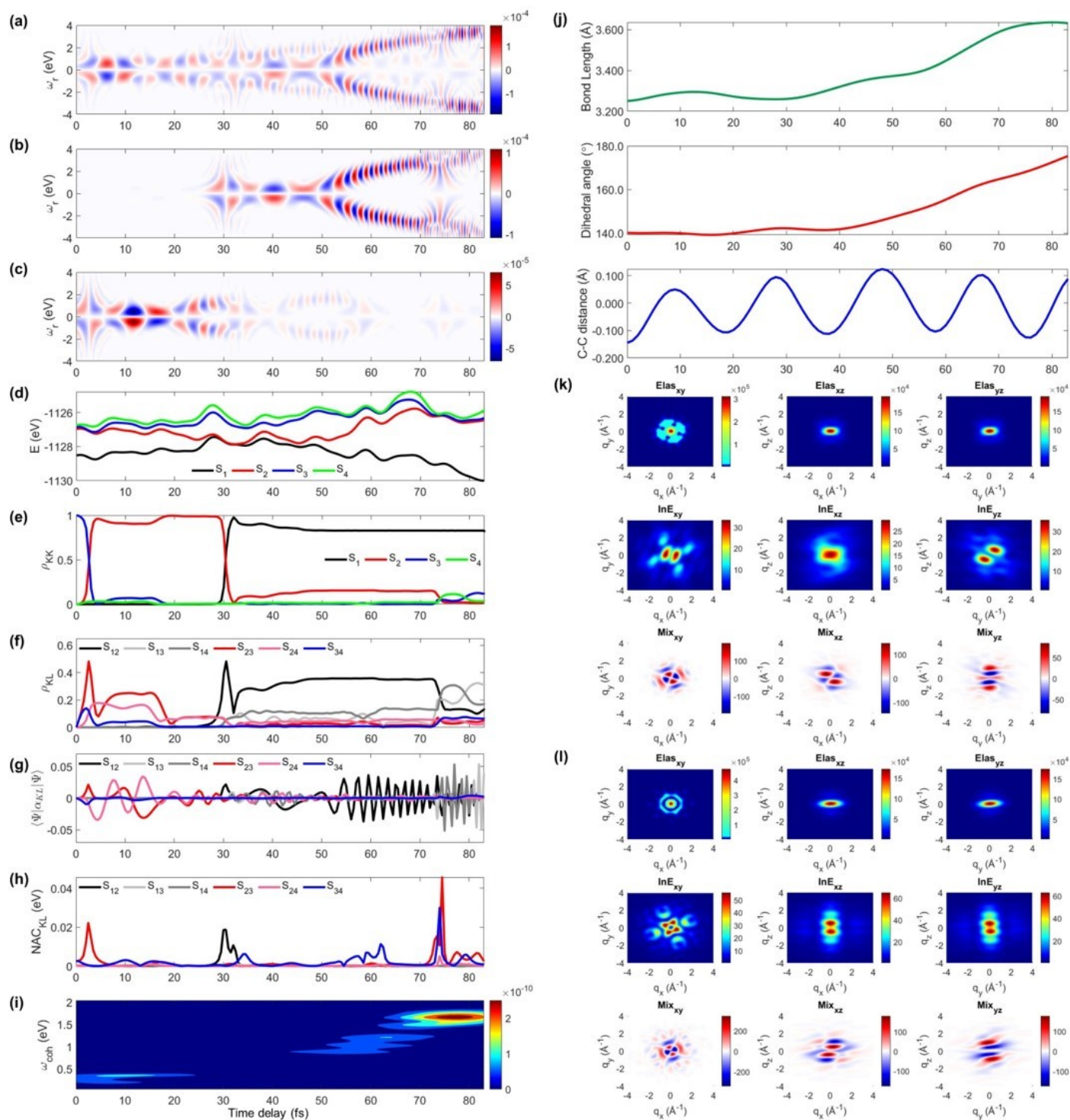


Fig. 3 The TRUECARs and TRXD signal and relevant molecular properties in trajectory 1. The frequency-dispersed TRUECARs signal  $S(\omega_r, T)$ , for (a) Total, (b)  $S_2/S_1$  coherence, (c)  $S_3/S_2$  coherence. (d) Potential energy surfaces of the excited states. (e) Population in the electronic states (f) Coherence magnitude  $\rho_{KL}$ . (g) The expectation value of the polarizability operator. (h) Nonadiabatic coupling magnitude for each coherence  $\rho_{KL}$ . (i) Integrated FROG spectrogram. (j) Time evolution of molecular geometry, bond length (top), dihedral angle (middle), and bond alternation (bottom). (k) Two-dimensional TRXD scattering pattern at  $T=1$  fs. (l) same as (k) but at  $T=83$  fs.

photochemical reactions.

## 4 Methods

The excited state non-adiabatic dynamics of COT is calculated using the ab initio multiple cloning (AIMC)<sup>60,61</sup> approach implemented in the Non-adiabatic EXcited state Molecular Dynamics





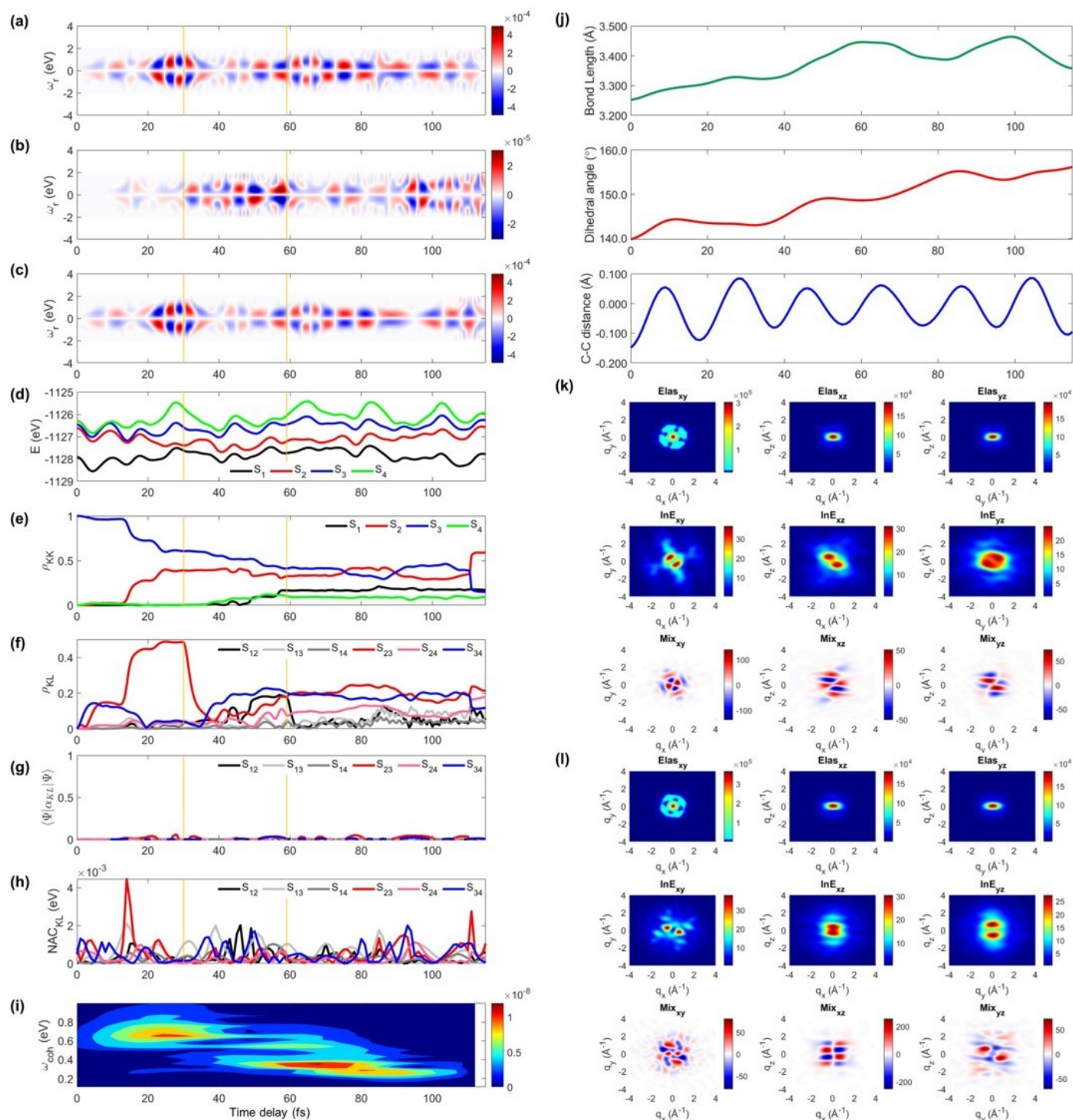


Fig. 4 Same as Fig. 3 but for trajectory 2. The yellow vertical lines mark the cloning events. The 2D TRXD pattern shown in (l) is plotted at  $T = 115$  fs.

(NEXMD) package<sup>62</sup>. This is an extension of the Multiconfigurational Ehrenfest (MCE)<sup>63</sup> method, which follows the spirit of the Ab Initio Multiple Spawning (AIMS) approach<sup>64</sup>, allowing bifurcations of the molecular wave function in the nuclear configuration space thus naturally accounting for decoherences. Details about the connection between these two similar approaches can be found elsewhere<sup>65</sup>. For AIMC, ensembles of individual Ehren-

fest trajectories (clones) are used as basis functions to represent the quantum wave function of electrons and nuclei  $|\Psi(t)\rangle$ <sup>66</sup>:

$$|\Psi(t)\rangle = \sum_n c_n |\psi_n(t)\rangle. \quad (1)$$

Each configuration  $\psi_n(t)$  is factorized into a nuclear part  $\chi_n(t)$  and orthonormalized adiabatic multi-configuration electronic eigen-

functions  $\phi_I^{(n)}$ :

$$|\Psi_n(t)\rangle = |\chi_n\rangle \left( \sum_I a_I^n(t) |\phi_I^n\rangle \right). \quad (2)$$

The nuclear wavepacket  $\chi_n(t)$  in each configuration is given by a Gaussian function centered at the Ehrenfest trajectory.

Population transfer between electronic states can occur during CI passages, where the Born Oppenheimer approximation breaks down and the motions of electron and nuclei are strongly coupled. The original nuclear wave packet branches into multiple parts, where the excess energy follows the different relaxation pathways, each dominated by a single adiabatic state. In such cases, Ehrenfest trajectories evolving on an average potential energy surface can lead to unphysical nuclear motions. AIMC recognizes these cases and replaces the original Ehrenfest trajectory configuration, with two new configurations and coefficients, each evolving along its own distinct mean-field. This splitting is denoted as cloning event, which allows to naturally account for decoherence of vibronic wavepackets evolving on the sufficiently different potential energy surfaces. More details of the AIMC method and its implementation can be found in Ref<sup>67,68</sup>.

The coherences between electronic states are given by:

$$\rho_{KL} = \frac{1}{2} \sum_{m,n} c_m^* c_n \langle \chi_m | \chi_n \rangle \sum_I \left[ (a_K^m)^* (a_L^n) \langle \phi_L^m | \phi_I^n \rangle + (a_L^m)^* (a_K^n) \langle \phi_I^m | \phi_K^n \rangle \right] \quad (3)$$

The phases of both the electronic and the nuclear parts of the molecular wave function are accounted for when calculating the vibronic coherence magnitude  $\rho_{KL}$ .

The TRUECARs signal is finally given by:<sup>26</sup>

$$S(\omega_s, T) = 2\text{Im} \int dt \mathcal{E}_B^*(\omega_s) \mathcal{E}_N(t-T) e^{i\omega_s(t-T)} \langle \Psi(t) | \alpha | \Psi(t) \rangle \quad (4)$$

where "Im" denotes the imaginary part,  $\mathcal{E}_{N/B}$  is a hybrid narrow (2 femtosecond)/broadband (500 attosecond) Gaussian pulse envelope (Figure 1a),  $\omega_s$  is the central probe frequency,  $T$  is the time delay between the pump and the probe. The expectation value of the transition polarizability  $\langle \Psi(t) | \alpha_{KL} | \Psi(t) \rangle$  is given by

$$\begin{aligned} \langle \Psi(t) | \alpha_{KL} | \Psi(t) \rangle &= \frac{1}{2} \sum_{m,n} c_m^* c_n \langle \chi_m | \chi_n \rangle \\ &\times \left[ (a_K^m)^* \alpha_{KL}^m \sum_I a_I^n \langle \phi_L^m | \phi_I^n \rangle + a_L^n \alpha_{KL}^n \sum_I (a_I^m)^* \langle \phi_I^m | \phi_K^n \rangle \right] \end{aligned} \quad (5)$$

The transition polarizability  $\alpha_{KL}$  is calculated from the transition charge density,  $\sigma_{KL}$ , where

$$\sigma_{KL}(\mathbf{q}, \mathbf{R}) = \int d\mathbf{r} e^{-i\mathbf{q}\cdot\mathbf{r}} \sum_{rs} P_{rs}^{ij}(\mathbf{R}) \varphi_r^*(\mathbf{r}, \mathbf{R}) \varphi_r(\mathbf{r}, \mathbf{R}), \quad (6)$$

using the state charge density matrices  $P_{rs}^{ij}$ , and the basis set of atomic orbitals  $\varphi_r(\mathbf{r})$ . Populations do not contribute to the signal, since  $\alpha_{KK}$  is zero along the diagonal, and only the transition polarizabilities (off-diagonal elements) between electronic states are finite. The TRUECARs signal is calculated for a randomly oriented ensemble by averaging over the x, y, and z axes. We

shall display the frequency resolved optical-gating (FROG) spectrogram of the TRUECARs signal given by Ref<sup>58</sup>, by convolving a temporal trace  $S(t)$  at a constant  $\omega_r$ , with a Gaussian gating function  $E_{\text{gate}}(t)$  with a full width at half-maximum (fwhm) of 0.484 fs,

$$I_{\text{FROG}}(T, \omega_{\text{coh}}) = \left| \int_{-\infty}^{\infty} dt S(t) E_{\text{gate}}(t-T) e^{-i\omega_{\text{coh}} t} \right|^2. \quad (7)$$

$S(T)$  oscillates with frequencies that correspond to the energy splitting between the relevant vibronic coherences, and the FROG spectrogram reveals the transient energy splitting along the trajectory. The FROG spectrograms are scanned and integrated over negative Raman shift ( $\omega_r < 0$ ) window to capture the evolution of the signal away from  $\omega_r = 0$ .

The gas phase (single-molecule) TRXD signal of a sample with  $N$  non-interacting molecules reads<sup>33,69</sup>

$$S_1(\mathbf{q}, t) = N \int dt |E_p(t-T)|^2 \langle \sigma(-\mathbf{q}, t) \sigma(\mathbf{q}, t) \rangle \quad (8)$$

where,

$$\langle \sigma(-\mathbf{q}, t) \sigma(\mathbf{q}, t) \rangle = \sum_{m,n} c_m^* c_n \langle \chi_m | \chi_n \rangle \sum_{I,J,K} (a_I^m)^* a_J^n (\sigma_{IK}^m)^\dagger \sigma_{KJ}^n \quad (9)$$

where,  $\langle \phi_I^m | \sigma(-\mathbf{q}, t) | \phi_K^m \rangle = (\sigma_{IK}^m)^\dagger$  and  $\langle \phi_K^n | \sigma(\mathbf{q}, t) | \phi_J^n \rangle = \sigma_{KJ}^n$ . We refer the reader to the ESI for the derivation more in detail.)

AIMC simulations of COT have been performed at constant energy using a 0.05 fs time step. The initial conformational structures were sampled from a 520 ps ground-state adiabatic molecular dynamics trajectory in a vacuum using a Langevin thermostat at 300 K with a 0.1 fs time step<sup>56</sup>. Following a 20 ps equilibration period, 100 snapshots of geometries and velocities were harvested every 10 ps and used as the initial conditions for the AIMC non-adiabatic molecular dynamics simulation. Nuclear dynamics were simulated for all 42 nuclear degrees of freedom, from the initial excited state  $S_3$  state populated by an impulsive excitation. Note that  $S_1$  is a dark state and  $S_2$  and  $S_3$  are both bright degenerate states, but the latter has 6 times larger oscillator strength than  $S_2$  during the ground state dynamics (see Fig. 1e in Ref<sup>56</sup>). The  $S_4$  state is located 0.47 eV higher than  $S_{2/3}$ , thus one can safely exclude the excitation to the  $S_4$  by using spectrally narrow enough optical pump pulse. If we follow what Levine et al. had done in their butadiene work<sup>70</sup>, our initial condition should locate 14.3% of the population to  $S_2$  and the remaining major population to  $S_3$ . We do not expect substantial differences in TRUECARs and TRXD signal, but the relaxation timescale of COT could be a bit faster.

Excited state properties (e.g., energies, gradients, and non-adiabatic couplings) are calculated on-the-fly at the configuration interaction singles (CIS) level of theory using the semiempirical Austin model 1 Hamiltonian<sup>71</sup>. The non-adiabatic transitions to the ground state near  $S_0/S_1$  CI have an inherent superposition or multireference character which cannot be properly described with single-reference CIS, time-dependent Hartree Fock or time-dependent density functional theory due to an incorrect description of the topology of the CI near crossing (phase factors, etc)<sup>72-74</sup>. An alternative approach is "Open-GS" method<sup>75,76</sup> that enforces such transition to the ground state when the energy gap



between the ground and excited states are smaller than a certain threshold. Hence, we set up 0.1 eV threshold value for  $S_1/S_0$  CI description so that the AIMC simulation is terminated, once one of the clones reaches this point. Finally, 98 independent trajectories were averaged for further TRUECARs signal analysis, whereas 57 trajectories were used for TRXD signal. We found that TRXD computations require extremely large data storage (e.g., each trajectory occupies around 66 GB, largest one takes up 200 GB) but averaging over 57 trajectories is enough to get converged results for TRXD signals. The computations of TRUECARs signals are not subjected to such computational cost, and we averaged over all 98 trajectories.

The use of transition polarizabilities, though computationally demanding, gives more accurate results compared with our previous work, where we set  $\alpha_{KL}$  to be constant (geometry-independent) over the nuclear space, thereby reducing  $\langle \Psi(t) | \alpha | \Psi(t) \rangle$  to the overlap between the involved electronic states (vibronic coherence magnitude)<sup>30,31</sup>.

## Author Contributions

Y.N. calculated the X-ray signals and wrote the manuscript. H.S. simulated non-adiabatic molecular dynamics and wrote the manuscript. V.M.F. and S.F.-A. derived the TRUECARs and TRXD signal. D.K. helped in computing and analyzing TRUECARs signal and its spectrogram. J.Y.L. and S.T. supervised the project and wrote the manuscript. M.G. suggested cyclooctatetraene molecule and wrote part of introduction. S.M. designed and supervised the project and wrote the manuscript.

## Conflicts of interest

There are no conflicts to declare.

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## Notes and references

- G. A. Olah, *Accounts of Chemical Research*, 1971, **4**, 240–248.
- A. Pron and P. Rannou, *Progress in Polymer Science*, 2002, **27**, 135–190.
- Y. Nam, J. R. Rouxel, J. Y. Lee and S. Mukamel, *Phys. Chem. Chem. Phys.*, 2020, **22**, 26605–26613.
- M. N. R. Ashfold, M. Bain, C. S. Hansen, R. A. Ingle, T. N. V. Karsili, B. Marchetti and D. Murdock, *The Journal of Physical Chemistry Letters*, 2017, **8**, 3440–3451.
- A. Bhattacharjee, K. Schnorr, S. Oesterling, Z. Yang, T. Xue, R. de Vivie-Riedle and S. R. Leone, *Journal of the American Chemical Society*, 2018, **140**, 12538–12544.
- D. A. Hrovat and W. T. Borden, *Journal of the American Chemical Society*, 1992, **114**, 5879–5881.
- P. G. Wenthold, D. A. Hrovat, W. T. Borden and W. C. Lineberger, *Science*, 1996, **272**, 1456–1459.
- M. Garavelli, F. Bernardi, A. Cembran, O. Castaño, L. M. Frutos, M. Merchán and M. Olivucci, *Journal of the American Chemical Society*, 2002, **124**, 13770–13789.
- M. Garavelli, F. Bernardi, V. Moliner and M. Olivucci, *Angewandte Chemie International Edition*, 2001, **40**, 1466–1468.
- I. J. Palmer, I. N. Ragazos, F. Bernardi, M. Olivucci and M. A. Robb, *Journal of the American Chemical Society*, 1993, **115**, 673–682.
- F. Bernardi, M. Olivucci and M. A. Robb, *Chem. Soc. Rev.*, 1996, **25**, 321–328.
- H. E. Zimmerman and H. Iwamura, *Journal of the American Chemical Society*, 1970, **92**, 2015–2022.
- L. Li, M. Lei, Y. Xie, H. F. Schaefer, B. Chen and R. Hoffmann, *Proceedings of the National Academy of Sciences*, 2017, **114**, 9803–9808.
- I. Aprahamian, *ACS Central Science*, 2020, **6**, 347–358.
- A. A. S. Briquet, P. Uebelhart and H.-J. Hansen, *Helvetica Chimica Acta*, 1996, **79**, 2282–2315.
- H. J. Wörner, J. B. Bertrand, B. Fabre, J. Higuier, H. Ruf, A. Dubrouil, S. Patchkovskii, M. Spanner, Y. Mairesse, V. Blanchet, E. Mével, E. Constant, P. B. Corkum and D. M. Villeneuve, *Science*, 2011, **334**, 208–212.
- M. S. Schuurman and A. Stolow, *Annual Review of Physical Chemistry*, 2018, **69**, 427–450.
- D. Keefer, S. Thallmair, S. Matsika and R. de Vivie-Riedle, *Journal of the American Chemical Society*, 2017, **139**, 5061–5066.
- B. Gu, D. Keefer, F. Aleotti, A. Nenov, M. Garavelli and S. Mukamel, *Proceedings of the National Academy of Sciences*, 2021, **118**, e21116868118.
- H. Timmers, X. Zhu, Z. Li, Y. Kobayashi, M. Sabbar, M. Hollstein, M. Reduzzi, T. J. Martínez, D. M. Neumark and S. R. Leone, *Nature Communications*, 2019, **10**, 3133.
- J. Yang, X. Zhu, T. J. A. Wolf, Z. Li, J. P. F. Nunes, R. Coffee, J. P. Cryan, M. Gühr, K. Hegazy, T. F. Heinz, K. Jobe, R. Li, X. Shen, T. Veccione, S. Weathersby, K. J. Wilkin, C. Yoneda, Q. Zheng, T. J. Martinez, M. Centurion and X. Wang, *Science*, 2018, **361**, 64–67.
- C. Bressler and M. Chergui, *Chemical Reviews*, 2004, **104**, 1781–1812.
- E. Goulielmakis, Z.-H. Loh, A. Wirth, R. Santra, N. Rohringer, V. S. Yakovlev, S. Zherebtsov, T. Pfeifer, A. M. Azzeer, M. F. Kling, S. R. Leone and F. Krausz, *Nature*, 2010, **466**, 739–743.





- 24 A. Stolow, A. E. Bragg and D. M. Neumark, *Chemical Reviews*, 2004, **104**, 1719–1758.
- 25 D. Polli, P. Altoè, O. Weingart, K. M. Spillane, C. Manzoni, D. Brida, G. Tomasello, G. Orlandi, P. Kukura, R. A. Mathies, M. Garavelli and G. Cerullo, *Nature*, 2010, **467**, 440–443.
- 26 M. Kowalewski, K. Bennett, K. E. Dorfman and S. Mukamel, *Phys. Rev. Lett.*, 2015, **115**, 193003.
- 27 D. Keefer, T. Schnappinger, R. de Vivie-Riedle and S. Mukamel, *Proceedings of the National Academy of Sciences*, 2020, **117**, 24069–24075.
- 28 S. M. Cavaletto, D. Keefer and S. Mukamel, *Phys. Rev. X*, 2021, **11**, 011029.
- 29 Y. Nam, D. Keefer, A. Nenov, I. Conti, F. Aleotti, F. Segatta, J. Y. Lee, M. Garavelli and S. Mukamel, *The Journal of Physical Chemistry Letters*, 2021, **12**, 12300–12309.
- 30 D. Keefer, V. M. Freixas, H. Song, S. Tretiak, S. Fernandez-Alberti and S. Mukamel, *Chem. Sci.*, 2021, **12**, 5286–5294.
- 31 V. M. Freixas, D. Keefer, S. Tretiak, S. Fernandez-Alberti and S. Mukamel, *Chem. Sci.*, 2022, **13**, 6373–6384.
- 32 J. Cao and K. R. Wilson, *The Journal of Physical Chemistry A*, 1998, **102**, 9523–9530.
- 33 K. Bennett, J. D. Biggs, Y. Zhang, K. E. Dorfman and S. Mukamel, *The Journal of Chemical Physics*, 2014, **140**, 204311.
- 34 S. Bratos, F. Mirloup, R. Vuilleumier and M. Wulff, *The Journal of Chemical Physics*, 2002, **116**, 10615–10625.
- 35 M. Simmermacher, A. Moreno Carrascosa, N. E. Henriksen, K. B. Møller and A. Kirrander, *The Journal of Chemical Physics*, 2019, **151**, 174302.
- 36 G. Dixit, O. Vendrell and R. Santra, *Proceedings of the National Academy of Sciences*, 2012, **109**, 11636–11640.
- 37 A. Kirrander, K. Saita and D. V. Shalashilin, *Journal of Chemical Theory and Computation*, 2016, **12**, 957–967.
- 38 D. Arnlund, L. C. Johansson, C. Wickstrand, A. Barty, G. J. Williams, E. Malmerberg, J. Davidsson, D. Milathianaki, D. P. DePonte, R. L. Shoeman, D. Wang, D. James, G. Katona, S. Westenhoff, T. A. White, A. Aquila, S. Bari, P. Berntsen, M. Bogan, T. B. van Driel, R. B. Doak, K. S. Kjær, M. Frank, R. Fromme, I. Grotjohann, R. Henning, M. S. Hunter, R. A. Kirian, I. Kosheleva, C. Kupitz, M. Liang, A. V. Martin, M. M. Nielsen, M. Messerschmidt, M. M. Seibert, J. Sjöhamn, F. Stellato, U. Weierstall, N. A. Zatsepin, J. C. H. Spence, P. Fromme, I. Schlichting, S. Boutet, G. Groenhof, H. N. Chapman and R. Neutze, *Nature Methods*, 2014, **11**, 923–926.
- 39 K. J. Gaffney and H. N. Chapman, *Science*, 2007, **316**, 1444–1448.
- 40 M. P. Minitti, J. M. Budarz, A. Kirrander, J. S. Robinson, D. Ratner, T. J. Lane, D. Zhu, J. M. Glowonia, M. Kozina, H. T. Lemke, M. Sikorski, Y. Feng, S. Nelson, K. Saita, B. Stankus, T. Northey, J. B. Hastings and P. M. Weber, *Phys. Rev. Lett.*, 2015, **114**, 255501.
- 41 B. Stankus, H. Yong, N. Zotev, J. M. Ruddock, D. Bellshaw, T. J. Lane, M. Liang, S. Boutet, S. Carbajo, J. S. Robinson, W. Du, N. Goff, Y. Chang, J. E. Koglin, M. P. Minitti, A. Kirrander and P. M. Weber, *Nature Chemistry*, 2019, **11**, 716–721.
- 42 H. Yong, N. Zotev, B. Stankus, J. M. Ruddock, D. Bellshaw, S. Boutet, T. J. Lane, M. Liang, S. Carbajo, J. S. Robinson, W. Du, N. Goff, Y. Chang, J. E. Koglin, M. D. J. Waters, T. I. Sølling, M. P. Minitti, A. Kirrander and P. M. Weber, *The Journal of Physical Chemistry Letters*, 2018, **9**, 6556–6562.
- 43 J. Yang, R. Dettori, J. P. F. Nunes, N. H. List, E. Biasin, M. Centurion, Z. Chen, A. A. Cordones, D. P. Deponte, T. F. Heinz, M. E. Kozina, K. Ledbetter, M.-F. Lin, A. M. Lindenberg, M. Mo, A. Nilsson, X. Shen, T. J. A. Wolf, D. Donadio, K. J. Gaffney, T. J. Martinez and X. Wang, *Nature*, 2021, **596**, 531–535.
- 44 E. Biasin, Z. W. Fox, A. Andersen, K. Ledbetter, K. S. Kjær, R. Alonso-Mori, J. M. Carlstad, M. Chollet, J. D. Gaynor, J. M. Glowonia, K. Hong, T. Kroll, J. H. Lee, C. Liekhus-Schmaltz, M. Reinhard, D. Sokaras, Y. Zhang, G. Doumy, A. M. March, S. H. Southworth, S. Mukamel, K. J. Gaffney, R. W. Schoenlein, N. Govind, A. A. Cordones and M. Khalil, *Nature Chemistry*, 2021, **13**, 343–349.
- 45 P. Zalden, F. Quirin, M. Schumacher, J. Siegel, S. Wei, A. Koc, M. Nicoul, M. Trigo, P. Andreasson, H. Enquist, M. J. Shu, T. Pardini, M. Chollet, D. Zhu, H. Lemke, I. Ronneberger, J. Larsson, A. M. Lindenberg, H. E. Fischer, S. Hau-Riege, D. A. Reis, R. Mazzarello, M. Wuttig and K. Sokolowski-Tinten, *Science*, 2019, **364**, 1062–1067.
- 46 Y. Lee, J. G. Kim, S. J. Lee, S. Muniyappan, T. W. Kim, H. Ki, H. Kim, J. Jo, S. R. Yun, H. Lee, K. W. Lee, S. O. Kim, M. Cammarata and H. Ihee, *Nature Communications*, 2021, **12**, 3677.
- 47 E. Biasin, T. B. van Driel, K. S. Kjær, A. O. Dohn, M. Christensen, T. Harlang, P. Vester, P. Chabera, Y. Liu, J. Uhlig, M. Pápai, Z. Németh, R. Hartsock, W. Liang, J. Zhang, R. Alonso-Mori, M. Chollet, J. M. Glowonia, S. Nelson, D. Sokaras, T. A. Assefa, A. Britz, A. Galler, W. Gawelda, C. Bressler, K. J. Gaffney, H. T. Lemke, K. B. Møller, M. M. Nielsen, V. Sundström, G. Vankó, K. Wärnmark, S. E. Canton and K. Haldrup, *Phys. Rev. Lett.*, 2016, **117**, 013002.
- 48 K. Haldrup, G. Levi, E. Biasin, P. Vester, M. G. Laursen, F. Beyer, K. S. Kjær, T. Brandt van Driel, T. Harlang, A. O. Dohn, R. J. Hartsock, S. Nelson, J. M. Glowonia, H. T. Lemke, M. Christensen, K. J. Gaffney, N. E. Henriksen, K. B. Møller and M. M. Nielsen, *Phys. Rev. Lett.*, 2019, **122**, 063001.
- 49 D. Keefer, F. Aleotti, J. R. Rouxel, F. Segatta, B. Gu, A. Nenov, M. Garavelli and S. Mukamel, *Proceedings of the National Academy of Sciences*, 2021, **118**, e2022037118.
- 50 J. R. Rouxel, D. Keefer, F. Aleotti, A. Nenov, M. Garavelli and S. Mukamel, *Journal of Chemical Theory and Computation*, 2022, **18**, 605–613.
- 51 T. R. Nelson, A. J. White, J. A. Bjorgaard, A. E. Sifain, Y. Zhang, B. Nebgen, S. Fernandez-Alberti, D. Mozyrsky, A. E. Roitberg and S. Tretiak, *Chem. Rev.*, 2020, **120**, 2215–87.
- 52 V. M. Freixas, A. J. White, T. Nelson, H. Song, D. V. Makhov, D. Shalashilin, S. Fernandez-Alberti and S. Tretiak, *The Journal of Physical Chemistry Letters*, 2021, **12**, 2970–2982.
- 53 J. T. O'Neal, E. G. Champenois, S. Oberli, R. Obaid, A. Al-Haddad, J. Barnard, N. Berrah, R. Coffee, J. Duris, G. Gali-



- nis, D. Garratt, J. M. Glowina, D. Haxton, P. Ho, S. Li, X. Li, J. MacArthur, J. P. Marangos, A. Natan, N. Shivaram, D. S. Slaughter, P. Walter, S. Wandel, L. Young, C. Bostedt, P. H. Bucksbaum, A. Picón, A. Marinelli and J. P. Cryan, *Phys. Rev. Lett.*, 2020, **125**, 073203.
- 54 D. Cho, J. R. Rouxel and S. Mukamel, *The Journal of Physical Chemistry Letters*, 2020, **11**, 4292–4297.
- 55 Y. Nam, F. Montorsi, D. Keefer, S. M. Cavaletto, J. Y. Lee, A. Nenov, M. Garavelli and S. Mukamel, *Journal of Chemical Theory and Computation*, 2022, **18**, 3075–3088.
- 56 H. Song, Y. Nam, D. Keefer, M. Garavelli, S. Mukamel and S. Tretiak, *J. Phys. Chem. Lett.*, 2021, **12**, 5716–22.
- 57 K. Kosma, S. A. Trushin, W. E. Schmid and W. Fuß, *Chemical Physics*, 2015, **463**, 111–119.
- 58 R. Trebino, K. W. DeLong, D. N. Fittinghoff, J. N. Sweetser, M. A. Krumbügel, B. A. Richman and D. J. Kane, *Review of Scientific Instruments*, 1997, **68**, 3277–3295.
- 59 S. M. Cavaletto, D. Keefer, J. R. Rouxel, F. Aleotti, F. Segatta, M. Garavelli and S. Mukamel, *Proceedings of the National Academy of Sciences*, 2021, **118**, e2105046118.
- 60 V. M. Freixas, S. Fernandez-Alberti, D. V. Makhov, S. Tretiak and D. Shalashilin, *Phys. Chem. Chem. Phys.*, 2018, **20**, 17762–72.
- 61 H. Song, V. M. Freixas, S. Fernandez-Alberti, W. A. J., Y. Zhang, S. Mukamel, N. Govind and S. Tretiak, *J. Chem. Theory Comput.*, 2021, **17**, 3629–43.
- 62 W. Malone, B. Nebgen, A. White, Y. Zhang, H. Song, J. Bjorggaard, A. Sifain, B. Rodriguez-Hernandez, V. Freixas, S. Fernandez-Alberti, E. Roitberg, R. Nelson and S. Tretiak, *J. Chem. Theory Comput.*, 2020, **16**, 5771–83.
- 63 D. V. Shalashilin, *The Journal of Chemical Physics*, 2009, **130**, 244101.
- 64 M. Ben-Nun, J. Quenneville and T. J. Martínez, *The Journal of Physical Chemistry A*, 2000, **104**, 5161–5175.
- 65 B. F. E. Curchod and T. J. Martínez, *Chemical Reviews*, 2018, **118**, 3305–3336.
- 66 S. Fernandez-Alberti, D. V. Makhov, S. Tretiak and D. V. Shalashilin, *Phys. Chem. Chem. Phys.*, 2016, **18**, 10028–40.
- 67 D. V. Makhov, W. J. Glover, T. J. Martinez and D. V. Shalashilin, *The Journal of Chemical Physics*, 2014, **141**, 054110.
- 68 D. V. Makhov, K. Saita, T. J. Martinez and D. V. Shalashilin, *Phys. Chem. Chem. Phys.*, 2015, **17**, 3316–3325.
- 69 K. Bennett, M. Kowalewski, J. R. Rouxel and S. Mukamel, *Proceedings of the National Academy of Sciences*, 2018, **115**, 6538–6547.
- 70 B. G. Levine and T. J. Martínez, *The Journal of Physical Chemistry A*, 2009, **113**, 12815–12824.
- 71 J. J. P. Stewart, *J. Mol. Model.*, 2004, **10**, 155–64.
- 72 B. G. Levine, C. Ko, J. Quenneville and T. J. Martínez, *Molecular Physics*, 2006, **104**, 1039–1051.
- 73 L. Stojanović, S. Bai, J. Nagesh, A. F. Izmaylov, R. Crespo-Otero, H. Lischka and M. Barbatti, *Molecules*, 2016, **21**, 1603.
- 74 S. M. Parker, S. Roy and F. Furche, *Phys. Chem. Chem. Phys.*, 2019, **21**, 18999–19010.
- 75 Y. Zhang, S. Mukamel, M. Khalil and N. Govind, *Journal of Chemical Theory and Computation*, 2015, **11**, 5804–5809.
- 76 F. Furche and J. P. Perdew, *The Journal of Chemical Physics*, 2006, **124**, 044103.

