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Electron-flux infrared response to varying \( \pi \)-bond topology in charged aromatic monomers

Héctor Álvaro Galué\(^1\), Jos Oomens\(^{1,2}\), Wybren Jan Buma\(^1\) & Britta Redlich\(^2\)

The interaction of delocalized \( \pi \)-electrons with molecular vibrations is key to charge transport processes in \( \pi \)-conjugated organic materials based on aromatic monomers. Yet the role that specific aromatic motifs play on charge transfer is poorly understood. Here we show that the molecular edge topology in charged catacondensed aromatic hydrocarbons influences the Herzberg-Teller coupling of \( \pi \)-electrons with molecular vibrations. To this end, we probe the radical cations of picene and pentacene with benchmark armchair- and zigzag-edges using infrared multiple-photon dissociation action spectroscopy and interpret the recorded spectra via quantum-chemical calculations. We demonstrate that infrared bands preserve information on the dipolar \( \pi \)-electron-flux mode enhancement, which is governed by the dynamical evolution of vibronically mixed and correlated one-electron configuration states. Our results reveal that in picene a stronger charge \( \pi \)-flux is generated than in pentacene, which could justify the differences of electronic properties of armchair- versus zigzag-type families of technologically relevant organic molecules.
A challenge in the innovation of molecular organic electronics is to understand the fundamental physical principles controlling charge transport\(^1\). Significant efforts have focused on acene\(^2\) aromatic hydrocarbons consisting of fused benzenoid rings arranged in centrosymmetric linear structures. Acenes are key monomeric building blocks for designing prototypical organic solids as the number of rings defines the electronic band structure\(^3\) via the extent of molecular $\pi$-conjugation or delocalization (in which overlapping $p_z$ atomic orbitals interconnect electrons across rings). Another approach to organic electronics is offered by phenacenes\(^4\) which are non-centrosymmetric versions of acenes consisting of rings fused in angular-oriented structures. Illustrative examples in the case of molecular crystal structures based on acenes and phenacenes show diverse electronic properties\(^3\)-\(^9\) ranging from semiconducting to metallic and even superconducting. In particular, pentacene of five linearly fused rings, is a common active compound used in field-effect semiconductors\(^6\). The semiconducting phenacene counterpart of pentacene is picene, which exhibits important differences in charge mobility and electronic stability\(^7\)-\(^10\).

A more intriguing distinction between the two monomers is the reported superconductivity of metal-doped picene solids, which is absent in pentacene analogues\(^9\),\(^11\)-\(^13\). While the crystal configuration (for example, lattice, doping, chemical-group functionalization) and operational conditions govern the conductivity in the above examples, one can expect that the intrinsic picene and pentacene molecular structures play a decisive role as well.

Presently, a molecular-level picture reconciling the differences in electronic properties is lacking. Yet, a recognizable influential factor on these properties is the vibronic coupling of molecular vibrations with $\pi$-electron molecular orbitals\(^12\),\(^14\)-\(^18\) inherent to the $\pi$-bond-edge topology\(^19\). To gain insight in the role of this topology in picene and pentacene vibronic behaviours, we probe here their monomeric structures in the positive charge state (picene\(^+\), pentacene\(^+\)) using infrared multiple-photon dissociation action spectroscopy\(^20\),\(^21\). This spin-doublet cationic state, featuring an unpaired electron in the highest-occupied molecular orbital, vibronically coupled with electronic states associated with excitation to low-lying unoccupied molecular orbitals of the proper symmetry. In our experiments we isolate gas-phase cations in an ion trap and probe them with infrared photons from the Dutch free-electron laser (FEL) for infrared experiments. By means of resonant multiple-photon vibrational excitation, we record photodissociation spectra as we tune the FEL photon energy. This high-sensitivity technique helps us circumvent the issue of undetectable direct absorptions of the low-density ion samples that result from electrostatic repulsion.

Although quantification of action spectra can be non-trivial due to the multiple-photon dissociation dynamics\(^20\),\(^22\), the central thesis here is the isomeric correspondence between picene and pentacene in which multiple-photon dissociation channels have spectral responses affected by alike intrinsic kinetics. Thus, in this case, action spectra of two species can be compared quantitatively provided that the spectra are measured under similar experimental settings.

The spectra of both cationic systems show substantial infrared activity in the 1,100–1,600 cm\(^{-1}\) range, which we ascribe to electronic density oscillations during antisymmetric C=C stretch vibrational excitation. The driving vibronic mechanism\(^23\)-\(^28\) arises in the molecular dipole moment (\(\mathbf{\mu}\)) derivative along the nuclear displacement normal-coordinate \(Q_k\) of the infrared intensity equation (ref. 27) \(I_k = (8\pi^2N_eV_0/3h)[V_{\text{i}}(\partial^2/\partial Q_0^2)Q_k(V_0/2\hbar)^2\), where the vibrational wavefunctions \(V_0\) and \(V_1\) characterize the fundamental harmonic dipole transition (1 $\leftrightarrow$ 0) of \(\nu_k\)th mode. The second term of the molecular dipole \(\mathbf{\mu} = q_N(r) + \langle \mathbf{\Psi}_g(r)\rangle\) (\(-e\mathbf{r}\langle \mathbf{\Psi}_g(r)\rangle\)) is the non-classical dipolar part of ground-state electrons described by the Born–Oppenheimer wavefunction \(\mathbf{\Psi}_0\) and \(R\) being the electronic and nuclear coordinates, and \(q_N\) being the nuclei dipole. By equating a first-order expansion of \(\mathbf{\Psi}_0\) with respect to nuclear normal coordinates \(Q\) (Supplementary Note 1) into \(\mathbf{\mu}\) we write \(\partial \mathbf{\mu}/\partial Q_k\) as a sum of two sources of infrared activity\(^24\),\(^28\),

\[
\frac{\partial \mathbf{\mu}}{\partial Q_k} = \frac{\partial}{\partial Q_k} \left[ q_N + \langle \mathbf{\Psi}_0 | -e \mathbf{r} | \mathbf{\Psi}_0 \rangle \right] + 2 \sum_{\xi=i} \frac{\langle \mathbf{\Psi}_0 | (\partial H/\partial Q_{0\xi})| \mathbf{\Psi}_1 \rangle}{E_i - E_0} \langle \mathbf{\Psi}_0 | \mathbf{r} | \mathbf{\Psi}_1 \rangle,
\]

where single (one-electron) configuration wavefunctions \(\mathbf{\Psi}_0/\mathbf{\Psi}_1\) (evaluated at equilibrium nuclear positions) and energies \(E_{0/1}\) correspond to ground (o) and excited (i) adiabatic states (\(\xi\)). The matrix elements \(\langle \mathbf{\Psi}_0 | (\partial H/\partial Q_{0\xi})| \mathbf{\Psi}_1 \rangle\) and \(\langle \mathbf{\Psi}_0 | \mathbf{r} | \mathbf{\Psi}_1 \rangle\) are the Herzberg–Teller vibronic coupling strength and electronic transition, respectively, and \(H\) is the electronic Hamiltonian. The first static-charge term arises from oscillating nuclei and nuclei-fixed electrons, while the second charge-flux term of oscillating non-fixed electrons is the vibronically active contribution of low-lying electronic excited states mixing into the ground state.

We show that the vibronic contribution to the picene\(^+\) infrared spectrum can be twice as large as in the pentacene\(^+\) spectrum, which is attributed to stronger dipole $\pi$-electron fluxes in the former system. Quantum-chemical calculations support this conclusion but also reveal that electronic correlation is essential to describe the intense C=C stretch $\pi$-flux modes of picene\(^+\). Whereas the multiple-photon dynamics impedes extracting absolute magnitudes of the underlying $\pi$-fluxes in picene\(^+\) and pentacene\(^+\), by virtue of comparing their multiple-photon dissociation yields we are able to discern molecular charge-flux effects (driven by vibronic coupling) on the resultant action spectra. We show that within the used FEL settings, the recorded action bands scale quasi-linearly with FEL average power and are satisfactorily described under the harmonic approximation as corroborated by quantum-chemical theory (apart from the anharmonic band broadenings inherent to the multiple-photon excitation process). We assert that the ability of picene to enable a significant dipolar $\pi$-flux charge separation, as manifested in the infrared action bands, is a general characteristic of aromatic motifs with armchair-edge topology. The fundamental distinction found here between picene and pentacene provides a dynamical charge-flux—structure relation useful to rationalize charge transport phenomena in $\pi$-conjugated organic materials built from aromatic structures.

**Results**

**Molecular structures.** We first examine the structural edge topology\(^22\) (Fig. 1a) in terms of $\pi$-electron delocalization. With zigzag edges, pentacene has only one resonant ring sextet of interconnected $\pi$-electrons\(^33\), while the other 16 non-sextet $\pi$-electrons tend to stay within bonds. Conversely, the picene armchair edges enable three $\pi$-sextets to resonate into adjacent rings\(^33\), and this fact fosters an aromatic system in which delocalization extends over the entire structure. This justifies the higher stability of neutral picene over pentacene by 0.68 eV calculated by density functional theory (B3LYP/6-311G\(^\ast\)\(*\)). The degree of $\pi$-delocalization is then inherently different in both systems as reflected in the $\pi$-electron spin-orbital wavefunctions. Figure 1b shows the energetic orderings with different spacing of frontier molecular $\pi$ spin-orbitals. The orderings define the electronic configurations of cationic spin-doublet ground states (\(D_{\text{a}}\)) \(^2\text{B}_1\) and \(^2\text{B}_{2g}\) of picene\(^+\) and pentacene\(^+\), respectively, and
of low-lying excited states accessible via $\pi \to \pi^*$ excitations (Supplementary Tables 1 and 2). Experimentally, we produce pentacene and picene radical cations (C$_{22}$H$_{14}$$^+$) by non-resonant two-photon ionization$^{34}$ of the neutral precursors at 193 nm (Fig. 2).

**Infrared action spectra.** A FEL macropulse resonantly energizes the initially thermal population (Supplementary Fig. 1) of mass-isolated C$_{22}$H$_{14}$$^+$ parent ions (picene$^+$ or pentacene$^+$) via absorption of several tens of infrared photons resulting in dissociation to product ions C$_{20}$H$_{14}$$^+$ and C$_{18}$H$_{10}$$^+$ (Fig. 2b,d). Note that the fast intramolecular vibrational energy redistribution (IVR $\gg$10$^9$ s$^{-1}$) among normal modes ensures statistical allocation of the energy of each absorbed photon prior to dissociation$^{35}$, as well as the resonant absorption at fundamental transitions$^{36,37}$. Under the FEL settings of our experiments, resonant excitation by the FEL induces competing dissociation kinetics of C$_{22}$H$_{14}$ and C$_{18}$H$_{10}$ via the lower energy loss channel (Fig. 2b). The signal of the dominant C$_{22}$H$_{14}$$^+$ loss channel typically comprises only 2 and 7% of picene$^+$ and pentacene$^+$ thus obviating the occurrence of dissociation yield band saturations around the band characterizations in Supplementary Tables 3–6).

The final action spectra plotted along wavelength or frequency (Figs 2c and 3) result from averaging various dissociation yield functions $\beta(\lambda)$ retrieved from the product ion signals recorded along FEL photon energy (Methods). The final average of both systems is corrected for FEL power variation and normalized to 1. The two spectra include a low-energy range extending down to 400 cm$^{-1}$. The power correction normalizes the band intensities from different spectral scans as measured in independent FEL-ion-trap experimental sessions. The precision in our measurements is discussed below for a data set sample of single scans (Supplementary Fig. 2). Apart from the large random noise component and slight variations in band broadening, each single spectrum in the sample exhibits similar infrared absorption features as confirmed by the partial spectra averages featuring reduced random noise level (Supplementary Figs 3 and 4 with band characterizations in Supplementary Tables 3–6).

The statistical random noise in each one-scan spectrum produces somewhat diverse baselines upon dividing by the FEL power curve (hence, averaging usually precedes the power correction). Also, the high noise in each spectrum impedes performing the spectral deconvolution curve fitting since the parameter initialization (based on the initial guess of band peak positions) fails. We thus obtain the frequency ($\tilde{\nu}_{\text{exp}}$) and intensity ($\beta$) band values manually. Despite the inaccuracy added by this human factor, the statistics from the data sample provides a notion of the precision between measurements. The $\tilde{\nu}_{\text{exp}}$ (and $\beta$) band characterizations are $a_1$: 1,567 ± 19 cm$^{-1}$ (0.50 ± 0.10), $a_2$: 1,512 ± 17 cm$^{-1}$ (0.73 ± 0.09), $b_1$: 1,338 ± 10 cm$^{-1}$ (0.61 ± 0.05),

- **Figure 1 | Investigated monomers and frontier $\pi$ spin-orbital energy levels.** (a) Chemical structures of picene (D$_{2h}$ symmetry) and pentacene (C$_{2v}$ symmetry) featuring delocalized sextet rings of six $\pi$-electrons (dotted inner circles). (b) Energy-level configurations of molecular $\pi$ spin-orbitals in the cationic spin-doublet ground state (B3LYP/6-311G**). The energy gaps between spin-orbitals are governed by cross-link bond electrostatic interactions$^{19}$. The vertical cross-link bonding between two zigzag edges causes out-of-phase atomic-orbital combinations$^{32}$ that tend to disperse frontier spin-orbitals, while the interaction between armchair edges takes place through inner ca. 120° angle-oriented cross-linkage of in-phase character, resulting in spin-orbitals that bear close proximity or even accidental degeneracy. Dotted arrows show main vibronically active transitions$^{36,37}$. Under the FEL settings of our experiments, resonant excitation by the FEL induces competing dissociation$^{35}$, as well as the resonant absorption at fundamental transitions$^{36,37}$. Under the FEL settings of our experiments, resonant excitation by the FEL induces competing dissociation$^{35}$, as well as the resonant absorption at fundamental transitions$^{36,37}$.
that the two product ions (both exhibit same spectral features) arise from the same parent; hence, the possible event of sequential photon absorption

\[ \text{m/z } 226 \] ion signals recorded continuously along tuned FEL photon energy (action bands characterized in Table 1). (d) Proposed scheme of multiple-photon induced dissociation kinetics along the potential energy reaction profile (reaction coordinate from left to right) connecting the reactant \( C_{22}H_{14}^+ \) parent ion (as transition state \( E^0 \)) with \( C_{22}H_2^+ \) product ion (A), the intermediate isomerization\(^{32} \) product ion (B), and the \( C_{22}H_2^+ \) loss product ion (\( C_{16}H_8^{+} \)). The energy barriers \( E_1, E_{iuv}, \) and \( E_2 \) correspond to first \( C_{22}H_2^+ \) loss (1), isomerization and second \( C_{22}H_2^+ \) loss (2) reactions. Figure 6 confirms that the two product ions (both exhibit same spectral features) arise from the same parent; hence, the possible event of sequential photon absorption by the intermediate B structure does not influence the spectra.

**Harmonic analysis.** Although the multiple-photon excitation relies on the anharmonic character of IRV coupled modes, which could induce noticeable nonlinear effects, there are examples such as the naphthyl \(^+ \) action spectrum\(^{38,39} \) confirming the quasi-resonant harmonic description of adiabatic molecular potentials probed by multiple-photon action spectroscopy\(^{37,40} \). Here, the bands observed in the action spectra are summarized in Table 1 with their spectral deconvolutions and harmonic mode assignments (from Supplementary Tables 7–16) based on the B3LYP vibrational analysis of Fig. 3. Both cations feature a very intense high-energy 1,600–1,100 cm\(^{-1} \) region of \( a, b \) and \( c \) bands, and a relatively weak mid-energy 1,100–700 cm\(^{-1} \) region of \( d, e \) and \( f \) bands. The band decompositions in Fig. 3a,f reveal the extent to which individual normal modes contribute to action bands. The mean value of absolute shifts between action and harmonic band frequencies is 1.43 ± 0.9% in \( \text{picene}^+ \) and 1.19 ± 0.79% in \( \text{pentacene}^+ \). The larger total shift in \( \text{picene}^+ \) reflects the contribution of the \( C_2H_2^+ \) loss dissociation channel (larger than in \( \text{pentacene}^+ \)) for which high activation energy brings larger anharmonic shifts\(^{20} \) (vide infra).

Despite the higher symmetry in \( \text{pentacene}^+ \), its action spectrum reveals more spectral congestion than \( \text{picene}^+ \) action spectrum as confirmed by its bigger number of fitted peak components (Fig. 3a,f). The high-energy range of \( b_2- \)symmetry modes in \( \text{picene}^+ \) and \( b_2- \)symmetry modes in \( \text{pentacene}^+ \) comprises, respectively, 92% and 88% of the total infrared activity (Supplementary Table 17). Generally, \( b_2 \) and \( b_2- \) modes involve \( C=\text{C} \) stretching motions antisymmetric with respect to the molecular \( xz \) plane, and are susceptible to vibronic couplings with low-lying \( \pi \)-orbitals. The band decompositions show that the intense vibronically active modes \( \nu_{78} \) and \( \nu_{84} \) in \( \text{picene}^+ \) are responsible of bands \( a \) and \( b \) (see Fig. 3a,e), whereas the strongest mode \( \nu_{85} \) in \( \text{pentacene}^+ \) generates band \( b \) (Fig. 3f,j). Next to

\[ b: 1,281 ± 9 \text{ cm}^{-1} (0.75 ± 0.05), \]
\[ b: 1,212 ± 8 \text{ cm}^{-1} (0.62 ± 0.04), \]
\[ c: 1,141 ± 10 \text{ cm}^{-1} (0.56 ± 0.07) \]
\[ \text{for } \text{picene}^+, \] and \( a: 1,448 ± 16 \text{ cm}^{-1} (0.45 ± 0.06), \]
\[ b: 1,313 ± 9 \text{ cm}^{-1} (0.78 ± 0.09), \]
\[ c: 1,163 ± 7 \text{ cm}^{-1} (0.77 ± 0.09), \]
\[ e: 911 ± 7 \text{ cm}^{-1} (0.47 ± 0.05), \]
\[ f: 737 ± 4 \text{ cm}^{-1} (0.43 ± 0.04) \]
\[ \text{for } \text{pentacene}^+. \] These values are in fair agreement with the values determined via the more rigorous deconvolution procedure applied on sample averages (B2B3 and A for \( \text{picene}^+ \); D1D3D5 and D6D7 for \( \text{pentacene}^+ \)) featuring a reduced noise (Supplementary Tables 3–6), and with the values of the full data set average (Fig. 3). We establish that the \( \nu_{\text{exp}} \) and \( \beta \) band fluctuations are due to typical random changes during experiments rather than to systematic instrumental biases or uncharacterized molecular processes during ion trapping. Finally, note that averaging over the full data set reduces the noise component more than when averaging over partial data sets. Thus, the larger random errors in the partial spectra are reflected in the spectral curve fittings characterizing the measured bands. For \( \text{picene}^+ \) \( b \) band, the \( \nu_{\text{exp}} \) and \( \beta \) average values between B2B3 and A data samples are 1,279.5 ± 1.0 and 0.87. These values represent a deviation of 0.20 and 6.5% relative to final values (Table 1) and accounts in part for the higher random error of partial spectra. From D1D3D5 and D6D7 data samples of \( \text{pentacene}^+ \), the \( \nu_{\text{exp}} \) and \( \beta \) average is 1,317.5 ± 1.0 (0.89) and represents a random error deviation of 0.11% (5.3%).
Theoretical linear harmonic spectra (generated by convoluting scaled normal modes with a Lorentzian curve is depicted in black. In Table 1 resultant peaks are summarized and sequentially numbered from respectively, for picene and pentacene species of 10% that agrees with the prediction of 11%. This spectral shift translates into a 39% increase in restoring force.

Electronic correlation. The dipolar charge redistribution along any vibration in both monomers is governed by the molecular electronic wavefunction \( \Psi_g \) having a well-defined ground-state configuration (Supplementary Tables 1 and 2). Within the so-called crude adiabatic approximation this ground-state configuration is defined at the equilibrium position \( Q_{\text{eq}} \) and is assumed to be independent of nuclear coordinates. For some modes, however, a proper description of \( \Psi_g \) requires other configurations describing low-lying excited states to be incorporated. Its dynamical evolution along a relevant normal coordinate \( Q_k \) is thus better described by the correlated configuration interaction of ground and excited configurations belonging, in this case, to a spin-doublet electronic manifold. Here we study the role of this electronic correlation on infrared spectra (generated by convoluting scaled normal modes with a Lorentzian curve), results from photoexcitation at out-of-plane C–H vibrations (cm\(^{-1}\)) of (a) picene\(^+\) and (f) pentacene\(^+\). The spectral deconvolution band fitting based on the Levenberg–Marquardt algorithm results, respectively, for picene\(^+\) and pentacene\(^+\), in 9 and 11 Lorentzian band peaks (each correspond to a lower case letter), which cumulative peak spectral curve is depicted in black. In Table 1 resultant peaks are summarized and sequentially numbered from 9 to 10 in correspondence with action band features. Theoretical linear harmonic spectra (generated by convoluting scaled normal modes with a Lorentzian 30 cm\(^{-1}\) function) are based on ROHF (b, picene\(^+\) and g, pentacene\(^+\)) and B88, BLYP and B3LYP density functionals (see Methods, mode assignations in Supplementary Tables 7–16 where B is B88) for c–e, picene\(^+\) and h–j, pentacene\(^+\).

As seen later, the relatively high intensities of \( f \) and \( e \) bands (see \( \beta/I_{\text{rat}} \) ratios, Table 1) arise equally in picene\(^+\) and pentacene\(^+\) from an increased ion production through the C\(_2\)H\(_2\)-loss dissociation channel at these low excitation energies.
The comparison between experimental and theoretical spectra show that the mean-field theory diverges more severely in picene, particularly in the C = C stretch high-energy region, supporting the need for electron correlated dynamics to properly describe its modes. This suggests that picene wavefunction readily interacts with certain excited electronic configurations during C = C stretch nuclear displacements, described in this case by 2b1-symmetry normal modes, which is a clear signal of vibronic activity (see next section). The 2b1-mode v9g exhibits for instance an unusual mean-field intensity of ca. 4.000 km mol−1 (Fig. 3b) since the ROHF method is unable to simulate the effective intramolecular electric field responsible for the generated dipole derivative. However, the density functionals rectify the odd intensities as corroborated by the experimental spectrum. Despite not including explicit vibronic treatments, their better performance is explained by the fact that density functionals implement local and non-local exchange-correlation interactions based on the single-valued electronic density42,43. In this sense, including gradient-density corrections (which account for density fluctuations emerging from low-lying excited configurations) further rectify the C = C stretch band pattern in agreement with the measured relative strengths of picene bands a and b, for example, B88→B3LYP (Fig. 3c,e). For pentacene, the spectroscopic comparisons suggest an evolution of its wavefunction Ψg along normal modes that roughly can be described by a single configuration; yet, some degree of correlated configuration interaction is required to reproduce the intensities of high-energy b2u modes.

For the out-of-plane C−H bending modes of the mid-energy region, all methods predict similar infrared activities except for some mode frequency shifts. The mean-field intensities of modes carrying e and f bands are 61 and 110 km mol−1 for v9g and v97 in pentacene, and 68 and 112 km mol−1 for v9g and v98 in picene. These intensities agree with B3LYP intensities (Table 1), showing that out-of-plane infrared-active modes are invariant to the level of theory.

**Vibronically driven π-fluxes.** The previous section shows that electron–electron correlated interactions are required for a proper description of dipole derivatives for C = C stretch b2γ-modes of picene, and to a certain extent, also for C = C stretch b2γ-modes of pentacene. Such electronic correlation manifests itself in equation (1) as non-negligible vibronic matrix elements that represent a configuration-interaction expansion of excited-to-ground state mixing coefficients. Together with the electronic matrix term, they comprise the vibronic dipolar term enabling molecular π-electron fluxes. To elucidate the physics of dipolar π-fluxes we first analyse the symmetry properties of both matrix elements. In the analysis, we consider the modes v94 and v84 responsible for the action band b of picene and pentacene, respectively, since their largest infrared strengths (Table 1) suggest significant dipolar π-flux contributions to action spectra at comparable FEL excitation energies (ΔEexp(b) = 2.88). Figure 4 shows key π−π* excitations in both systems for which electronic configurations are included in Supplementary Tables 1 and 2. In view of the energy denominator in equation (1) one expects that the electronic wavefunction of picene is most susceptible to mixing with the Ψg(4a2→4b1) excited configuration (Fig. 4a). On departure from its equilibrium geometry picene thus needs to be described as a linear combination of ground and excited configurations Ψg ≃ Ψ0(g|B1) + c1 Ψg(4a2→4b1), where the

Table 1 | Infrared multiple-photon action bands of picene and pentacene.

<table>
<thead>
<tr>
<th>Band</th>
<th>v_exp</th>
<th>β</th>
<th>Peak</th>
<th>v_cal</th>
<th>ε</th>
<th>w</th>
<th>A</th>
<th>h</th>
<th>L_cal</th>
<th>I_cal</th>
<th>v(4)</th>
<th>v(5)</th>
<th>v(6)</th>
<th>v(7)</th>
<th>Ia</th>
<th>Ib</th>
<th>I_b</th>
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<tbody>
<tr>
<td>a</td>
<td>1,513</td>
<td>0.91</td>
<td>1</td>
<td>1,591</td>
<td>2</td>
<td>199</td>
<td>10</td>
<td>91</td>
<td>0.3</td>
<td>1573</td>
<td>19</td>
<td>0.31</td>
<td>v9g(b2)</td>
<td>1,577</td>
<td>1250</td>
<td>-</td>
<td></td>
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<tr>
<td>a</td>
<td>1,535</td>
<td>0.75</td>
<td>3</td>
<td>1,347</td>
<td>1</td>
<td>111</td>
<td>63</td>
<td>43</td>
<td>0.21</td>
<td>1374</td>
<td>19</td>
<td>0.32</td>
<td>v8b(b2)</td>
<td>1,357</td>
<td>935</td>
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<td></td>
</tr>
<tr>
<td>b</td>
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<td>4</td>
<td>1,282</td>
<td>0</td>
<td>822</td>
<td>92</td>
<td>52</td>
<td>0.48</td>
<td>1318</td>
<td>19</td>
<td>0.18</td>
<td>v84(b2)</td>
<td>1,318</td>
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<td></td>
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<tr>
<td>b</td>
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<td>84</td>
<td>44</td>
<td>0.41</td>
<td>1232</td>
<td>0.4</td>
<td>v93(b2)</td>
<td>1,232</td>
<td>97</td>
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<td></td>
</tr>
<tr>
<td>c</td>
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<td>6</td>
<td>1,132</td>
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<td>19</td>
<td>0.3</td>
<td>1131</td>
<td>0.23</td>
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<td>190</td>
<td>0.27</td>
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<td>7</td>
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<td>84</td>
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<td>1,164</td>
<td>185</td>
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<td></td>
</tr>
<tr>
<td>e</td>
<td>823</td>
<td>0.23</td>
<td>8</td>
<td>823</td>
<td>0</td>
<td>67</td>
<td>72</td>
<td>25</td>
<td>0.15</td>
<td>820</td>
<td>0.26</td>
<td>v88(b1)</td>
<td>818</td>
<td>64</td>
<td>-0.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f</td>
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<td>0.15</td>
<td>745</td>
<td>0.27</td>
<td>v89(b2)</td>
<td>747</td>
<td>89</td>
<td>-1.07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The D2h point-group symmetry of pentacene is conserved after ultraviolet photoionization, so pentacene normal modes are classified in 8 symmetry representations (Γ) as 18αb + 7δb + 9δb + 17δb + 8αb + 17δb + 17δb + 9δb. Likewise, the modes of C2v-symmetry picene are 3αa + 17αb + 16b + 34b. The column headings are action band label (Band), action band peak frequency (v_cal cm−1), normalized dispersion yield (β). The deconvoluted spectral band peak components (Peak) are obtained by fitting a Lorentzian function y = y_ex + (A(x)/w(x)) to band features using a Levenberg-Marquart algorithm. The peak parameters with errors s.e. (C, significance level 5%) are central frequency (v0, cm−1): full-width at half maximum (ε), area (A), and height (h, 2A/ε w). The offsets (ε) are 0.002 (picene) and 0.0035 (pentacene). The statistics of the fits are Δf/2, 2R2(COD) = 0.96649, Reduced χ2 = 0.00008 (picene), and df = 2760, R2(COD) = 0.96268, and Reduced χ2 = 0.00026 (pentacene). The theoretical quantum-chemical quantities are calculated band peak frequency (v_cal cm−1), calculated band relative intensity (I_cal), normal mode (νb), normal mode frequency (νn, cm−1), and infrared mode oscillator-strength (E_km mol−1). The report band frequency shift deviations (β) relative to the calculation and experimental-to-theoretical relative intensity ratios (β_cal/cm).
pentacene, one-carbon density centers determine, respectively, the bonding and anti-bonding electronic characters of the excited spatial redistributions. Molecular side features an accumulation (scaling by a factor of 4) of bonding hand parts of picene during the vibronic mixing of \( \Psi \). We begin with picene coupling phases between the excited \( \psi \) generated. The symmetry of excited states promoting slightly unsynchronized in a way that it generates a \( \psi \)-density build-up (scaling by a factor of 2) with some neutralization at the center (note the relatively small inner-ring two-carbon centers located at opposite mirrored sides). This analysis indicates that the \( \psi \)-flux strength in picene is twice as much as in pentacene, which is in good agreement with the predicted infrared-strength ratio of \( \psi \) over \( \psi \) (pentacene) modes \( \psi \). We thus conclude that the dipolar source of these two \( \psi \) = \( \psi \) \( \psi \) modes is entirely due to the charge \( \psi \)-flux.

Experimentally, we observe in the action spectra a similar twofold \( \psi \)-flux enhancement once we calibrate the spectra that have been previously normalized on the intensity of band \( b \) with maximum absolute dissociation yield. To this end, we consider the intrinsic relation between \( b \) and \( b \) bands to be preserved in each system and then renormalize the spectra such that \( \beta \) = \( \beta \) \( \psi \) \( \psi \) (0.24/0.93)\( \beta \)\( \psi \) \( \psi \) = (0.52/0.94)\( \beta \)\( \psi \) \( \psi \) \( \psi \) (Table 1). We have used the mid-energy band \( b \) since in both systems this band is carried by intrinsically equivalent out-of-plane \( \psi \)--\( \psi \) bending modes. Solving for \( \beta \)\( \psi \) results in 2.15\( \beta \)\( \psi \) \( \psi \), which remarkably agrees with the strength ratio \( \psi \) \( \psi \) and thus, confirms the twofold increase of \( \psi \)-flux strength in picene.

Degree of nonlinearity in action spectra. The above analysis shows that relative intensities of action bands \( b \) and \( b \) can be described under the linear-absorption harmonic approximation. However, we have noticed that action spectra are inherently susceptible to nonlinearities as introduced by the multiple-photon dissociation (Fig. 2b,d). Moreover, relative intensities are based on dissociation yield functions that have been power-corrected and normalized, and these procedures could have brought an accidental agreement to the harmonic ratio \( \psi \). Therefore, to estimate the extent of these effects, we compare spectra from control measurements at high-energy FEL macropulses with a spectra sample from the final average of Fig. 3. Note that the spectra retrieved from the control measurements are not part of the final average.

We first compare in Fig. 6 the \( \psi \) and \( \psi \) loss ion signals of picene \( \psi \) recorded at 0 and 3 dB FEL power levels (signal and band characterizations in Supplementary Tables 18–20). The signal ratio \( \psi \)\( \psi \)\( \psi \)\( \psi \)\( \psi \)\( \psi \)\( \psi \) loss is found approximately constant along FEL photon energy (Fig. 6), suggesting that \( \psi \) and \( \psi \) loss rates evolve in quasi-linear proportion to each other. On
attenuation (3 dB), the mean value of the hence (quasi-)constant ratio of 1.73 changes to 2.52 always in favour of C$_2$H$_2$ loss. It is clear that at reduced macropulse energies, the energized molecular ion population reaches a lower average internal energy ($E$). This leads to a lower dissociation rate and eventually shuts down dissociation into the C$_2$H$_2$-loss channel with higher activation energy (that is, the inequality $E - E_{1} - E_{iso} < E_{2}$ is fulfilled, see Fig. 2d). At the lowest FEL photon energies (ca. 900 cm$^{-1}$) the ratio deviates from linearity towards C$_2$H$_2$ loss. For instance at the peak of band $f$, the ratio drops from 2.37 to 3.28 (Supplementary Table 20). Here the production of C$_4$H$_4$-loss ions drops as much as 38% while for C$_2$H$_2$-loss it drops only 14%. Comparing with band $a$, C$_2$H$_2$ and C$_4$H$_4$ losses decline by 30% and 45%, respectively. Despite the uneven variations between channels at band $f$, Fig. 6 does suggest that the dissociation yield $f$ decreases linearly on attenuation, revealing the determining role of C$_2$H$_2$-loss in the action spectra.

Whereas multiple-photon excitation with lower-energy macropulses decreases the C$_2$H$_2$ and C$_4$H$_4$ loss ion productions at $f$, $e$ and $a$ bands (an exception is band $e$ C$_2$H$_2$-loss, which retains the 0 dB signal), the C$_2$H$_2$ loss increases 17% at band $b$. This 17% increment is close to the observed 14% decrement of C$_4$H$_4$ loss (also at band $b$) suggesting linearly inverted dissociation kinetics between channels. Specifically for pentacene $^+$, we observe that C$_4$H$_4$ loss marginally varies on FEL irradiation along the tuned range, which correlates with the relatively lower oven temperatures set for sublimation. This shows that most energized pentacene $^+$ ions have an average internal energy just above the C$_2$H$_2$-loss activation energy (Fig. 2d). Because C$_2$H$_2$-loss steers the multiple-photon dissociation kinetics in both systems, their dissociation yields along excitation have a strong C$_2$H$_2$-loss signal component, from which nonlinear effects are recognized to be much smaller than the inherent differences between the two molecular systems.

**Power dependence of action band intensities.** To test whether nonlinear effects on band intensities are negligible, we retrieve the spectra from the ion signals of Fig. 6 (Fig. 7a,b; band decompositions in Supplementary Tables 21 and 22). The resultant yield functions $\beta ^*(i)$ are not normalized nor corrected for FEL power variations (as a function of excitation energy) to perform absolute comparisons between band intensities at 0 and 3 dB power levels. Table 2 lists four bands with their frequency peak ($\nu$exp), absolute yield (\$)^r$ and average power ($P$). The yield variation upon FEL attenuation is taken as a power-law function $\beta ^*(P) = CP^m$ (C and $m$ are constant and exponent factors). As seen in Fig. 6 for band $f$, a twofold power reduction (corresponding to a macropulse energy change from 42 to 20.8 mJ) brings a linear twofold yield change, that is, $m = 1$. For bands $a$ and $e$ the variations are nearly linear ($m = 0.8$). For band $b$ we find a non-linear behaviour ($m = 0.1$) as expected from the reversed 17% increasing signal behaviour of C$_2$H$_2$-loss as we reduce the macropulse energy (Fig. 6).
Comparing the absolute band yields of picene $^+$ with those of pentacene $^+$ (Fig. 7c, Supplementary Table 23) measured at the lower FEL power values reveals a reasonable agreement (compare Fig. 7b,c). The pentacene $^+$ $f$ yield intensity (0.00894) recorded at 26 mJ (260 mW) linearly scales to 0.0072 at 20.8 mJ in fair agreement with picene $^+$ $f$ yield 0.0077 recorded at 20.8 mJ (Table 2). This resemblance confirms the equal theoretical infrared strengths of their photoexcited modes ($\nu_{9g}$ in picene $^+$ and $\nu_{9g}$ in pentacene $^+$). For band $e$, we expect some deviation given the difference in excitation energies between picene $^+$ and pentacene $^+$ for this band (frequency deviation of $\Delta \nu_{\text{exp}}(e) = 10\%$ from Table 1), which suggests somewhat different anharmonic couplings. Indeed, at 19.3 mJ the pentacene $^+$ $e$ yield (measured at 23.9 mJ) scales to 0.0060 whereas the picene $^+$ $e$ yield is 0.0071 (Table 2).

For band $b$, the similar excitation energies required in both parent ions ($\Delta \nu_{\text{exp}}(b) = 2.8\%$) suggest that absolute yields could be comparable at the lower FEL power values (Fig. 7b,c). The $b$ yields are 0.0125 and 0.0153 recorded at 17.8 and 9.9 mJ for pentacene $^+$ and picene $^+$, respectively. For pentacene $^+$, the $b$
Table 2 | Absolute dissociation yield band intensities versus FEL average power.

<table>
<thead>
<tr>
<th>Infrared band</th>
<th>$v_{\text{exp}}$ (cm$^{-1}$)</th>
<th>P (mW)</th>
<th>$b^*$</th>
<th>$\Delta v_{\text{exp}}$ (%)</th>
<th>$P_0/P_{\text{lab}}$</th>
<th>$b^<em>_{\text{o-avg}}/b^</em>_{\text{lab}}$</th>
<th>$m$</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1,489</td>
<td>43</td>
<td>0.0063</td>
<td>0.20</td>
<td>1.91</td>
<td>1.64</td>
<td>0.8</td>
<td>0.0004</td>
</tr>
<tr>
<td></td>
<td>1,492</td>
<td>82</td>
<td>0.0103</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>1,219</td>
<td>99</td>
<td>0.0153</td>
<td>0.99</td>
<td>2.01</td>
<td>1.06</td>
<td>0.1</td>
<td>0.0103</td>
</tr>
<tr>
<td></td>
<td>1,207</td>
<td>199</td>
<td>0.0162</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>824</td>
<td>193</td>
<td>0.0071</td>
<td>0.73</td>
<td>2.01</td>
<td>1.76</td>
<td>0.8</td>
<td>1E – 04</td>
</tr>
<tr>
<td></td>
<td>818</td>
<td>388</td>
<td>0.0125</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>741</td>
<td>208</td>
<td>0.0077</td>
<td>0.81</td>
<td>2.02</td>
<td>2.02</td>
<td>1.0</td>
<td>4E – 05</td>
</tr>
<tr>
<td></td>
<td>735</td>
<td>420</td>
<td>0.0155</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Infrared band characteristics of action spectra of Fig. 7a,b. The column headings are action band label (Infrared band), action band peak frequency ($v_{\text{exp}}$), FEL average power (P), or macropulse energy ($P_0/P_{\text{lab}}$), absolute dissociation yield intensity ($b^*$), band peak frequency shift deviation ($\Delta v_{\text{exp}}$), FEL average power ratio ($P_0/P_{\text{lab}}$), yield ratio ($b^*_{\text{o-avg}}/b^*_{\text{lab}}$). The parameters of a fitted absolute-yield-intensity-power-law ($P^{b^*} = C P^{3d B}$) of $C$ factors. Given the large frequency deviation between high- and low-power band a peaks ($\Delta v_{\text{exp}}/11\%$), the lower-power band characterization is done at $P_0/P_{\text{lab}}=2$ (1.91). The $a$ band $b^*$ value thus differs from the one reported in Supplementary Table 22.

Discussion

We have deduced the relative strength between vibronic $\pi$-flux contributions to modes $v_{\text{a4}}$ and $v_{\text{b5}}$ generating the action band $b$ of picene$^+$ and pentacene$^+$, respectively. Within our FEL macropulse settings, the picene$^+$-to-pentacene$^+$ $b$ band ratio is satisfactorily explained under the harmonic approximation which predicts an intensity ratio $I_{\text{b}}/I_{\text{ab}}$ of 2.06 (at B3LYP/6-311G** level of theory). This means that a harmonic Hamiltonian can describe the molecular potential along action band $b$ vibrations. One last question relates to the effects of spectral convolution on band intensities. On the basis of the heights (h) of deconvoluted peaks for $f$ and $b$ bands, we estimate an experimental band ratio of 2.41 (where we subtracted the 0.035 offset for pentacene$^+$ peaks, see Table 1). This value deviates by 12% from the first value obtained from relative intensities in Fig. 3. The better agreement in the first estimation could be due to an error cancelation on averaging over the full data set, but also, it could reflect the absolute intensity difference of picene$^+$ (0.0077) and pentacene$^+$ (0.0072) $f$ bands. Nonetheless, the fair agreement between action and harmonic band intensity ratios ratifies the twofold $\pi$-flux increase in picene$^+$ compared with pentacene$^+$.

From our studies a picture emerges in which picene is able to generate a higher degree of dipolar charge separation along its monomeric structure than pentacene. We have argued that this is a direct consequence of the spatial dynamical evolution (via the adiabatic vibronic operator $\partial H/\partial Q_{\text{a4}}$) of mixed armchair-edge type electronic wavefunctions typical of angular-oriented aromatic structures. These armchair-edge wavefunctions are intrinsically strongly correlated. Thus, in the case of superconducting molecular crystals based on picene and related monomers$^9$, this evidence implies that both electron–phonon and electron–electron interactions could be at the origin of electron pairing. This work allows us to a closer vision the exploration of picene-like motifs in heterojunctions$^4$ or supramolecular nano-assemblies$^4$ of related devices, whose operation is triggered by photoinduced charge separation. Finally, note in equation (1) that larger vibronic couplings along modes of armchair-type monomers relative to zigzag-type monomers may not always translate into larger dipolar charge-flux contributions to the infrared spectra in the former class, since the vibronic coupling strength is weighted by the electronic transition matrix element. In conclusion, our results show that infrared multiple-photon action spectroscopy can deliver significant information on intramolecular charge dynamics when applied to charged molecular species with similar dissociation kinetics and vibrational resonances.

Methods

Free-Electron Laser for Infrared Experiments FELIX. In our experiments, FELIX delivered typically 7 μs long macropulses every 100 ms with transform-limited bandwidth of about 1% of the central $\lambda$ tuned in steps of 0.02 or 0.04 μm. Each macropulse consisted of 1 ps long micropulses at 1 GHz. A typical average energy at 13 μm was 42 mJ per macropulse, which delivers a fluence of 5.3 J cm$^{-2}$ in the center of the ion trap on a spot of 1-mm diameter. Nowadays, FELIX is located at Radboud University in Nijmegen (The Netherlands).

Infrared multiple-photon dissociation action spectroscopy. Action spectra are recorded with a Paul-type ion trap mass-spectrometer (Jordan TOF Products, Inc.) attached to a FELIX beaml ine$^{20,30}$. The ion trap built into a high vacuum chamber is made of a toroidal inner ring electrode of 2 cm inner diameter interposed between two hyperbolic endcap electrodes. The trap is biased at $+1.000$ VDC, setting a potential difference relative to a 60-cm length time-of-flight (TOF) mass spectrometer used for mass-to-charge (m/z) ion detection. Cations (m/z 278) of pentacene and picene are produced by 193 nm ultraviolet photoionization of gas-phase neutral molecules effused to the inner trap volume upon sublimation of solid samples (99.9% picene, TCI Europe; 99% pentacene, Sigma-Aldrich) with a built-in oven at temperatures as high as 200°C. The ultraviolet source is a 5-ns pulsed excimer laser (PSX-501 Neweks Ltd.) adjusted to a typical energy of 1.6 mJ per pulse and power density in the trap of $3 \times 10^{12}$ W cm$^{-2}$. For TOF mass analysis, axial extraction is achieved by switching off the RF voltage while applying a −250 VDC pulse to the endcap (with a 3 mm hole) closest to the TOF-tube. Ultraviolet photo-induced product ions below m/z 278 are ejected before FEL irradiation by a brief (2 ms) RF amplitude increase. After a few milliseconds after ionization of an ensemble of picene$^+$ (or pentacene$^+$) ions, FEL on-resonance irradiation at fundamental vibrational transitions induces multiple-photon dissociation. Two spherical mirrors (gold coated) are used to enhance the FEL fluence. A FEL-triggered delay generator (SRS-DG520) controls the 10 Hz experimental sequence. The recorded ion signals of parent and multiple-photon product ions are amplified and digitized (Acquisir). The pressure values in the high vacuum chamber were typically in the $10^{-6}$–$10^{-7}$ mbar range. We estimate the dissociation yield, $\rho(\lambda)$ or
Quantum chemical calculations. We obtained optimized electronic structures and harmonic vibrational mode frequencies using ab initio Hartree–Fock theory as the spin-restricted open-shell ROHF method\(^4\), and the local spin-density approximation (LSDA) plus a variety of exchange-correlation gradient-corrected functionals. These are the LSDA gradient-corrected exchange-only Becke-1988 functional\(^5\) (B88). The Becke-1988 method plus the gradient-corrected correlation LYP functional\(^6\) (BLYP), and the hybrid 3-21G functionals that include generalized exchange-correlation gradient corrections and some degree of exact Hartree–Fock exchange energy\(^7\) (B3LYP). The atomic-orbital basis set used is a split-valence triple-ζ Gaussian-type 6-31G with \(d\) and \(p\) polarization functions. The excited-state calculations were done at the B3LYP level after transposing the relevant spin-orbitals involved in the excitations. To reduce computational cost we used the smaller set 6-31G(\(d\)). All reported harmonic spectra were generated by convoluting normal modes with a Lorentzian 30 cm\(^{-1}\) bandwidth profile with frequencies scaled by 0.97 to account for basis-set truncation. The excited spatial distribution probabilities were obtained from Kohn–Sham spin-orbital \(\pi\) wavefunctions. We obtained the complex coupled \(\pi\) and the modulus \(|\pi| = |\pi_0|^{1/2} = |\pi_0|^{1/2} = |\pi_0|^{1/2}\). We performed all quantum-chemical calculations using Gaussian 09 (Frisch, M.J. et al. Gaussian 09, Revision A.02., 2010). The data supporting the findings of this study are available within the article, Supplementary Information, and if applicable, from the corresponding author on request.

**References**

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Author contributions

B.R. supervised, maintained and operated FELIX, and assisted in FELIX-ion-trap experiments. W.J.B. performed the calculations and analysis. J.O. supervised the research, performed analysis, and assisted in FELIX-ion-trap experiments. H.A.G. conceived the study, performed the FELIX-ion-trap experiments, calculations and analysis, and wrote the manuscript with inputs of W.J.B. and J.O.

Additional information

Supplementary Information accompanies this paper at http://www.nature.com/naturecommunications

Competing financial interests: The authors declare no competing financial interests.


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