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1. Introduction

The vacuum ultraviolet (VUV) photochemistry of small gasphase molecules can provide useful fundamental information for the studies of astrochemistry.^{1,2} The dynamics of highly excited electronic states caused by VUV radiation involves complicated nonadiabatic transitions, and sometimes the molecular photodissociation processes should be explained by different mechanisms.³ Thanks to the development of the generation of a VUV source based on a table-top laser system⁴⁻⁷ or large-scale scientific facility (e.g., the synchrotron radiation source⁸ or the VUV free-electron laser (FEL)^{9,10}), the VUV photochemistry of small molecules in the gas phase has been successfully explored over the past decades, especially in recent years. Among these previous studies, most of them were of frequency-domain, i.e., energy-resolved, and focused on small polyatomic molecules, such as diatomic and triatomic molecules. So far, the VUV photochemistry of aromatic heterocyclic



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We report the ultrafast decay dynamics of pyrrole upon excitation in the vacuum ultraviolet region using femtosecond time-resolved photoelectron spectroscopy in combination with two-photon absorption. With the two-photon pump energy up to ~6.78 eV, pyrrole is excited to the ¹B₂ valence and Rydberg states, *i.e.*, the first ¹B₂($\pi\pi^*$) valence state and the ¹B₂($\pi3d$) Rydberg state. The former is at high levels of vibrational excitation and has an extremely short lifetime of <30 fs, while the latter is in the vibrational ground state and decays with a lifetime of about 400 fs. As the excitation energy slightly increases, the ¹B₂($\pi3d$) vibrational states are populated and decay in 210–260 fs. We propose that the ultrafast deactivation pathway of the ¹B₂($\pi3d$) Rydberg state is internal conversion to the lower-lying ¹B₂($\pi\pi^*$) state. At higher excitation energies, other valence states, such as the second ¹B₂($\pi\pi^*$) state, should make a main contribution to the absorption and a series of other higher-lying Rydberg states with lifetimes of hundreds of femtoseconds are also involved. This study provides direct time-resolved measurements of subpicosecond excited-state lifetimes for high-lying Rydberg states in bare pyrrole.

molecules has been rarely investigated, especially using timeresolved ultrafast spectroscopy methods. Although some recent studies have reported the VUV excited state dynamics of representative small amides¹¹ and cyclic ethers¹² using time-resolved photoelectron spectroscopy (TRPES) in combination with ab initio electronic structure calculations, the understanding of the VUV photochemistry of important molecules is still limited by the availability of tunable VUV femtosecond pulses. For example, pyrrole (C₄H₅N) is one of the prototypical heteroaromatic molecules. The excited-state dynamics of isolated pyrrole following femtosecond pulse excitation in the ultraviolet (UV) pump wavelength range (≥ 200 nm) has been widely reported.^{13–20} However, in fact, the dynamics of higher-lying excited states of pyrrole in the VUV region has not been discussed in detail due to the lack of wavelength-tunable ultrafast VUV laser sources. As a special case, Weinacht and coworkers studied the relaxation dynamics of pyrrole after excitation with a 7.94 eV pump pulse to a state just 0.2 eV below the ionization potential in a previous VUV-pump UVprobe experiment,²¹ but the pump wavelength (156 nm) in their work was not tunable since it is the fifth-harmonic of a Ti:sapphire laser (780 nm).

In this paper, we present a femtosecond time-resolved study on the ultrafast decay dynamics of the highly excited states of pyrrole with the pump energy up to 6.2 eV (a spectral range of < 200 nm), by combining two-photon absorption and TRPES techniques in a similar way as that used in our previous studies of H₂O.^{22–24} Herein,

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Fig. 1 UV and VUV absorption spectrum of pyrrole adapted from ref. 25 (the data is obtained from https://www.uv-vis-spectral-atlas-mainz.org). A schematic structure of the pyrrole (C_4H_5N) molecule is inset.

the excitation energy-dependent decay dynamics of electronically excited pyrrole in the VUV wavelength range is explored for the first time by performing direct time-resolved pump-probe measurements. Of specific interest is the excited-state lifetimes of a series of Rydberg states and their deactivation pathways.

The UV and VUV absorption spectrum of pyrrole (Fig. 1) in the gas phase has been previously reported by Palmer and coworkers,²⁵ while the assignment of this spectrum has also been discussed in detail in their work and references therein. Briefly, in the case of pyrrole, there are four $\pi\pi^*$ electronic states, two each of which are of ${}^{1}A_{1}$ and ${}^{1}B_{2}$ symmetry (in $C_{2\nu}$), respectively. It has been concluded that each of the two strong absorption bands centred around 6 and 7.5 eV, respectively, owe their intensity to two $\pi^* \leftarrow \pi$ electronic transitions, *i.e.*, excitation of two $\pi\pi^*$ valence states of ${}^{1}A_1$ and ${}^{1}B_2$ symmetry. In addition, the valence transitions, along with a number of Rydberg excited states, should contribute to the narrow absorption peaks in the UV and VUV spectrum of pyrrole. Later on, a detailed analysis of the structure of pyrrole's electronic spectrum in the range of 5.5 to 6.5 eV was performed by Neville and Worth based on their quantum dynamics study.²⁶ Specifically, intensity borrowing from transitions to $\pi\pi^*$ states by lower-lying 3s and 3p Rydberg states was found to contribute significantly to much of the spectrum. In the current study, we focus solely on the VUV excited-state dynamics of pyrrole. In particular, according to the structure of the whole VUV absorption spectrum and the pump wavelength dependence on the TRPES spectra, we assign some absorption peaks to be associated with high-lying Rydberg states which have subpicosecond excited-state lifetimes. Our pump wavelength-dependent 2 + 1' TRPES study provides experimental evidence to support that high-energy excited pyrrole undergoes a complex relaxation dynamics with a fraction of the wavepacket being trapped in Rydberg states for hundreds of femtoseconds before further evolving to lower-lying valence states and the ground state. This proposed decay mechanism is in good agreement with a previous theoretical result obtained by performing non-adiabatic dynamics simulations of pyrrole.27

2. Experimental

The fs-TRPES experiment was carried out on a velocity map imaging (VMI) spectrometer.²⁸ The methods have been described

in detail elsewhere.^{29–32} Therefore, only the key features are presented here. A liquid sample of pyrrole (Adamas, \geq 99%) without further purification was loaded into an external sample reservoir and mixed with 4 bar of helium carrier gas at room temperature. The supersonic molecular beam was generated using an Even-Lavie pulsed valve operated at 1 kHz. The supersonic jet expansion entered into the interaction chamber of the VMI spectrometer through a 1 mm conical skimmer.

The wavelength-tunable femtosecond laser pulses were generated using two commercial optical parametric amplifiers (OPA, Coherent, OPerA Solo), each pumped by a fraction (1.1 mJ per pulse) of the fundamental output of the fully integrated Ti:sapphire oscillator-regenerative amplifier (Coherent, Libra-HE, 1 kHz, 800 nm, < 50 fs). In the 2 + 1' time-resolved pump-probe measurements (Fig. 2(a)), the two-photon pump energy should match the optical excitation of an electronically excited state with a specific lifetime. In the current study, different pump wavelengths in the range of 370-310 nm (broad spectral bandwidth) generated by doubling 740-620 nm using a 0.05 mm β -BBO crystal in OPA were employed. It should be pointed out that there always exists non-resonant (Fig. 2(b)) and resonant (Fig. 2(c)) multiphoton ionization process around the time-zero in a 2 + 1' ionization scheme. In order to avoid the unwanted signals generated from the probe-pump dynamics process (as illustrated in Fig. 2(d)) associated with the shortwavelength edge of the broad spectral bandwidth of the femtosecond probe laser pulses (two-probe-photon excitation of the S₁ state, *i.e.*, the ${}^{1}A_{2}(3s/\pi\sigma^{*})$ state), the probe laser was chosen in a specific wavelength range with its central wavelength being larger than 532 nm. For obtaining narrower bandwidth pump laser pulses, the pump laser beam was generated by doubling the output of one of the OPAs at 740-620 nm using a specific 2 mm β -BBO crystal.²⁴ Note that the shape of the spectra and pulse durations of these pump wavelengths deviate slightly from a perfect Gaussian profile. The pump and probe laser pulses were combined collinearly on a dichroic mirror without further compression, and then focused using a calcium fluoride lens (f = 30 cm) into the interaction region of the VMI spectrometer to intersect the seeded pyrrole molecular beam.

The pump pulses excited pyrrole molecules from their ground state to one or more electronically excited states by two-photon absorption, whereupon the delayed probe pulses produced photoelectrons via one-photon ionization. Both the pump and probe pulses were linearly polarized and the polarization direction was parallel to the micro-channel plate (MCP)/phosphor screen detector. The 2D photoelectron images at different time delays were recorded using a computercontrolled camera and further transferred to 3D distributions using the pBasex Abel inversion method.³³ The time-dependent photoelectron 3D distributions were integrated along the recoiling angle to derive the photoelectron kinetic energy distributions, i.e., TRPES. Additionally, the angular distributions of the emitted photoelectron, i.e., PADs, can be derived by integrating the 3D photoelectron distributions over a desired kinetic energy range and further analyzed in detail.31,34,35

3. Results and discussion

The absorption spectrum of pyrrole in the UV and VUV region (5-11 eV) has been previously measured using synchrotron radiation²⁵ and is reproduced using the open-access data from the MPI-Mainz UV/VIS Spectral Atlas,³⁶ as shown in Fig. 1. The main features of this observed spectrum are three absorption bands, which were denoted band 1, 2 and 3 in ref. 25. The interpretation of the first absorption band (5.5-6.6 eV) of this spectrum has been discussed,²⁵ while a detailed assignment has been given in the previous 1 + 1' TRPES and quantum dynamics studies.^{16,26} Herein we endeavor to explain the second and third absorption bands based on the result of the measured 2 + 1'TRPES data. Overall, the second absorption band (6.5-7.1 eV) is relatively weak and has a peak position of 182.6 nm, along with vibrational structure at excitation wavelengths shorter than ~180 nm, as shown in Fig. 3(a). In Fig. 3(c), the 2 + 1' TRPES spectrum of pyrrole at a pump wavelength of 368.0 nm is shown, while the spectrum of 368.0 nm (\sim 540 $\rm cm^{-1}$ at full width at halfmaximum (FWHM) due to the intrinsic broad spectral bandwidth of the femtosecond laser pulses) is plotted in Fig. 3(b). By visual inspection, the TRPES spectrum contains two different components. One component shows extremely fast decay dynamics over a broad photoelectron kinetic energy range and the other has a single strong and sharp peak centered at a specific kinetic energy, showing hundreds of femtoseconds decay dynamics. The relatively sharp photoelectron kinetic energy distribution should be due to the $\Delta v = 0$ Franck–Condon (FC) propensity in the photoionization process of a pure Rydberg state.^{34,35} In order to extract the lifetime information and their photoelectron kinetic energy distributions (so-called decay associated spectra), we employed a 2D global least-squares method to simultaneously fit the TRPES data at all time delays and photoelectron kinetic energies. Two different time constants of 23 ± 10 and 370 ± 30 fs (see Fig. S1 in the ESI⁺) could be

derived when we used the multi exponential decay model, which was achieved by a numerical convolution of the experimentally measured instrumental response function (IRF) and the exponential decay of excited state population. The approach has been described in much more detail in our recent papers.^{35,37,38}

As mentioned above, the femtosecond laser pulses with a relatively narrow bandwidth were also used as the pump laser for two-photon excitation. Their spectra (117–97 cm⁻¹ at FWHM) are shown in Fig. 3(b), together with the spectrum of 368.0 nm $(\sim 540 \text{ cm}^{-1})$. The TRPES spectra of pyrrole excited by twophoton absorption at 368.5, 365.9 and 364.8 nm are presented in Fig. 3(d-f). These TRPES spectra display different features and can be compared with each other. The main feature observed in the TRPES spectrum at 368.5 nm is a dominant component with a diffuse kinetic energy distribution, which even extends to higher kinetic energies above the 2 + 1' energetic cut-off (see Fig. S2(a) in the ESI⁺). This component shows less than tens of femtoseconds (*i.e.*, < 30 fs, 30 fs is \sim 25% of our 120 fs (FWHM) IRF based on an approximation of a Gaussian profile) dynamics, while the other component with a longer lifetime and a strong kinetic energy peak disappears. As the pump wavelength decreases to 365.9 nm, both components (<30 and 400 \pm 30 fs) make a contribution to the TRPES data. At 364.8 nm, the hundreds of femtoseconds (350 \pm 30 fs) component becomes dominant. Herein, as shown in Fig. S2(a) and (b) (ESI⁺), the < 30 fs component should contain the photoelectron signals generated from the 2 + 1' and 1 + 3' multiphoton ionization process around the time-zero (this process can be approximately described by the corresponding IRF), while the 2 + 1' pumpprobe process associated with the highly vibrationally excited ${}^{1}B_{2}(\pi\pi^{*})$ state can also make a contribution to this component at lower kinetic energies below the 2 + 1' energetic cut-off since it is reasonable to assume that the ${}^{1}B_{2}(\pi\pi^{*})$ vibrational states have a lifetime of <30 fs.^{18,19} Here the 1 + 3' process appears since the 1 + 2' three-photon energy is insufficient for photoionization of



Fig. 2 (a)–(c) Schematic representation showing the two-color 2+1' ionization processes in a time-resolved pump-probe experiment. (d) Schematic representation showing the two-color 1+2' ionization process (namely the probe-pump dynamics) which only appears when the two-probe-photon energy matches the absorption of an electronic excited state.



Fig. 3 (a) VUV absorption spectrum of pyrrole adapted from ref. 25 (the data is obtained from https://www.uv-vis-spectral-atlas-mainz.org) in a specific range of 179–188 nm. (b) Spectra of the pump wavelengths for two-photon excitation. (c)–(f) TRPES spectra of pyrrole excited by two-photon absorption at each pump wavelength, after subtracting the background photoelectrons generated from single-color multiphoton ionization.

pyrrole. By considering the calculated electronic excitation energies together with the oscillator strengths³⁹⁻⁴² and the two-photon pump energy dependence on the TRPES spectra in Fig. 3(c-f), it seems that the time constant of 350-400 fs can be assigned to the lifetime of the ${}^{1}B_{2}(1a_{2}3d_{yz})$ Rydberg state ($\nu' = 0$). Here this 3d-type Rydberg state $(3d_{xz}(b_1) \leftarrow \pi_{HOMO}(1a_2))$ is also termed simply ${}^{1}B_{2}(\pi 3d)$. However, for two-photon excitation, the ${}^{1}A_{2}(1a_{2}4s)$ Rydberg state ($\nu' = 0$) is also optically allowed (the 4s(a_1) $\leftarrow \pi_{HOMO}(1a_2)$) electronic transition is symmetry forbidden for one-photon absorption). We note that in an early one-color 2 + 1 resonance-enhanced multiphoton ionization (REMPI) spectrum of pyrrole, a very strong peak at 364.5 nm was observed⁴³ and assigned to be the origin of the ${}^{1}A_{2}(1a_{2}4s)$ Rydberg state.^{25,44} In our 2 + 1' TRPES spectra at pump wavelength of 365.9 and 364.8 nm for two-photon absorption, the contribution of the ${}^{1}A_{2}(1a_{2}4s)$ Rydberg state cannot be totally ruled out based on the analysis of the photoelectron kinetic energy distributions. It is impossible to distinguish the photoelectron signals ionized from the ${}^{1}B_{2}(1a_{2}3d)$ and ${}^{1}A_{2}(1a_{2}4s)$ states, respectively, since both excited states are of Rydberg character and their Rydberg state electron binding energies are too close.²⁵

Fortunately, in a REMPI study of jet-cooled pyrrole molecules using linear and circular polarized radiation,45 it was clearly evidenced that the dominant peak at 54 850 cm^{-1} (~6.80 eV) in the one-color 2 + 1 REMPI spectrum corresponds to a 3d $\leftarrow \pi$ transition, instead of a 4s $\leftarrow \pi$ transition. In our current pump-probe measurements, the photoelectron angular distributions (PADs) associated with oneprobe-photon ionization of this Rydberg state can be analyzed in detail thanks to using the femtosecond time-resolved photoelectron imaging (TRPEI) technique. In brief, the values of β_2 obtained from satisfactory fits to the corresponding PADs are negative, with an average value of about -0.29, as shown in Fig. S3 (ESI[†]). The limiting value of β_2 for a pure s-type Rydberg state is 2.0, together with the zero values of β_4 and β_6 , while the experimentally measured value of β_2 is reasonably close to 1.0.^{34,35} Therefore, the feature of these PADs (negative value of β_2) supports that the populated Rydberg state via two-photon resonant transition at \sim 364.8 nm should not mainly be the 4s-type Rydberg orbital.

It is interesting to note that in a previous femtosecond timeresolved work by Longarte and coworkers,¹⁵ a pyrrole⁺ transient collected with a (240 + 800 nm) pump/800 nm probe ionization scheme revealed a lifetime of hundreds of femtoseconds, which was not accurately assigned to a specific resonantly excited intermediate state. Based on our wavelength-dependent TRPES data here, we prefer to believe that 240 + 800 nm 1 + 1' excitation energy covers the ~6.78 eV absorption line of jet-cooled pyrrole molecules due to the intrinsic broad spectral bandwidth of their femtosecond laser pulses.

As the pump wavelength slightly decreases, the two-photon excitation energies cover the absorption peaks (174 nm $< \lambda <$ 182 nm), which were assigned to some vibrational states of the ${}^{1}B_{2}(\pi 3d)$ state, as illustrated in Fig. 4(a) and (b). The measured TRPES spectra of pyrrole excited by two-photon absorption at 359.9 nm (\sim 500 cm⁻¹) and 351.0 nm (\sim 440 cm⁻¹) are shown in Fig. 4(c) and (d), respectively. These 2 + 1' TRPES spectra can be compared with that at 368.0 nm (Fig. 3(c)). It is therefore straightforward to assign the derived time constants of 260 \pm 30 and 210 \pm 20 fs at 359.9 and 351.0 nm to the lifetimes of the ${}^{1}B_{2}(\pi 3d)$ vibrational states ($\nu' > 0$). The measurement of the electron kinetic energy (eKE) distribution allows us to determine the corresponding electron binding energy (eBE) of the molecular orbital of the excited state, from which the electron is ionized, i.e., eBE = $h\nu_{\rm probe}$ – eKE. The decay associated spectra of the hundreds of femtoseconds (210-400 fs) component are summarized in Fig. 5, where the energy axis is plotted in terms of eBE instead of eKE. Within the margin of error, the value of the peak position is invariant with the change of the pump wavelength, indicating that these photoelectron signals mainly correspond to the photoionization process of the same Rydberg state with different vibrational levels. The adiabatic excitation energy (AEE) of this Rydberg state is 6.79 \pm 0.01 eV



Fig. 5 Comparison of the decay associated spectra (DAS) of the second component (the value of τ is in a range of 210–400 fs) derived from a 2D global least-squares fit to the corresponding TRPES spectra shown in Fig. 3 and 4. The energy axis is plotted in terms of electron binding energy of the excited state.

calculated using the adiabatic ionization potential (IP_a) of pyrrole (8.21 eV (ref. 25)) and its 1.42 ± 0.01 eV electron binding energy, *i.e.*, AEE = IP_a – eBE. In addition, the geometry of this ¹B₂(π 3d) Rydberg state can be seen to be nearly the same as that of the ground state cation (D_0) based on the invariant 1.42 eV peak and its relatively narrow bandwidth, while there are some differences in the optimized geometries of the ground state of the neutral pyrrole molecule and D_0 .⁴⁶ Therefore, it is reasonable to assign the absorption peaks in the range of 174–182 nm to the photoexcitation of some vibrational levels of the ¹B₂(π 3d) Rydberg state. In addition, the relatively weak and diffuse



Fig. 4 (a) VUV absorption spectrum of pyrrole adapted from ref. 25 (the data is obtained from https://www.uv-vis-spectral-atlas-mainz.org) in a specific range of 168–188 nm. (b) Spectra of the pump wavelengths for two-photon excitation. (c) and (d) TRPES spectra of pyrrole excited by two-photon absorption at 359.9 and 351.0 nm, respectively, after subtracting the background photoelectrons generated from single-color multiphoton ionization.

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Fig. 6 (a) TRPES spectrum of pyrrole excited by two-photon absorption at 312.2 nm (\sim 38 cm⁻¹ at FWHM), after subtracting the background photoelectrons generated from single-color multiphoton ionization. Note that the energy axis is plotted as a function of electron binding energy of the excited state. (b) The electron binding energy distribution of the involved excited states derived by summing up the TRPES spectrum shown in (a) in a delay range of 0.21–1.20 ps.

distribution at higher electron binding energies larger than ~ 1.6 eV can be rationalized in simple terms of the existence of Rydberg-to-valence evolution, *e.g.*, the vibronic coupling between the ¹B₂($\pi\pi^*$) valence state and the ¹B₂($\pi3d$) Rydberg state in pyrrole.^{40–42} Therefore, in other words, the decay associated spectra shown in Fig. 5 are closely related to the energy-resolved photoionization cross sections of the electronic states involved in the dynamics,⁴⁷ *i.e.*, the ¹B₂($\pi3d$) and ¹B₂($\pi\pi^*$) states.

As the excitation energy further increases (*i.e.*, $\lambda < 174$ nm), the third absorption band (7-9 eV) of pyrrole becomes stronger and should be associated with a series of higher-lying Rydberg and valence type excited states.²⁵ The accurate assignments are complex and less clear-cut. This is consistent with our measured 2 + 1' TRPES spectra at pump wavelengths of 344-314 nm $(500-360 \text{ cm}^{-1})$, which exhibit different features. For example, at 337.7 nm (\sim 410 cm⁻¹), several Rydberg states such as 1a₂3d, $2b_13p/2b_13p'$, $1a_24p/1a_24p'$ and $1a_24d/1a_24d'$ seem to be involved in the dynamics of electronically excited pyrrole according to the excitation energies of these Rydberg states²⁵ and the derived Rydberg state electron binding energy distribution on the basis of the corresponding 2 + 1' TRPES spectrum (see Fig. S4 in the ESI[†]). More specially, our current study provides an opportunity to take a closer look at the pumpprobe pyrrole parent ion $(C_4H_5N^+)$ yield measurement in the previously mentioned 156 nm pump/260 nm probe experiment by Weinacht and coworkers.²¹ We employed 312.2 nm femtosecond laser pulses with a relatively narrow bandwidth of

 \sim 38 cm⁻¹ at FWHM as the pump wavelength. The 2 + 1' TRPES spectrum is shown in Fig. 6(a), while the excited state electron binding energy distribution derived by summing up this TRPES spectrum in a delay range of 0.21-1.20 ps is plotted in Fig. 6(b). The 1.42 eV peak corresponds to the electron binding energy of the ${}^{1}B_{2}(1a_{2}3d)$ Rydberg state and the 1.10 eV peak is ascribed to other Rydberg state(s), the adiabatic excitation energy of which is 0.32 eV higher than that of the ${}^{1}B_{2}(1a_{2}3d)$ state, ~6.78 eV. We note that the adiabatic excitation energies of two 4p Rydberg states are close to 7.10 eV. The origin of the ${}^{1}B_{2}(1a_{2}4p)$ and ${}^{1}B_{1}(1a_{2}4p')$ states are 7.096 and 7.120 eV, respectively, according to a previous assignment.²⁵ Therefore, we tentatively suggest that the photoelectron signal at the 1.10 eV Rydberg state electron binding energy peak is associated with the ionization of the vibrational states of the ${}^{1}B_{2}(1a_{2}4p)$ and ${}^{1}B_{1}(1a_{2}4p')$ Rydberg states. Both the 3d and 4p Rydberg states can have an excitedstate lifetime of hundreds of femtoseconds. The value of their lifetime slightly decreases with the increase of the vibrational excess energy. We conclude that more than one Rydberg state should be involved in the relaxation dynamics of pyrrole excited at 156 nm (7.94 eV), resulting in the real-time observation of the subpicosecond time constants in time-resolved measurements. More broadly speaking, the high-lying Rydberg series in pyrrole can play a role as a mediating state in the relaxation pathway of the $\pi\pi^*$ valence states. A similar mechanism has been previously proposed and experimentally evidenced in the case of a specifically selected ethylene-like molecule.48

4. Conclusions

In conclusion, we investigate the ultrafast decay dynamics of pyrrole molecules following femtosecond pulse two-photon excitation in the VUV wavelength range. Based on the detailed analysis of the 2 + 1' TRPES spectra and their excitation energy dependence, effort is devoted to the understanding of the VUV excited-state dynamics of pyrrole. The lifetimes of a series of high-lying Rydberg states are measured to be hundreds of femtoseconds. Internal conversion to nearby-lying valence states is suggested to be the dominant decay channel of these Rydberg states. This experimental 2 + 1' TRPES study provides valuable insights into the full picture of the VUV photodynamics of pyrrole.

Author contributions

Supervision: Guorong Wu and Xueming Yang; conceptualization: Dongyuan Yang and Guorong Wu; investigation: Dongyuan Yang and Yanjun Min; formal analysis: Dongyuan Yang, Yuhuan Tian and Zhigang He; discussion: all authors; writing: Dongyuan Yang; funding acquisition: Dongyuan Yang, Guorong Wu and Xueming Yang.

Data availability

All data supporting the findings of this study will be available on reasonable request. The data reproducing the UV and VUV absorption spectrum of pyrrole in this paper are open-access and can be obtained from https://www.uv-vis-spectral-atlasmainz.org.

Conflicts of interest

There are no conflicts to declare.

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