Resonance	E_Φ (eV)	q	Γ (meV)	τ (fs)
He sp2$^+$	60.15	-2.77	36	17
He sp3$^+$	63.66	-2.58	8	82

Table 1. Energy E_Φ, asymmetry parameter q, spectral width Γ and lifetime τ of the two autoionizing states of this study. Spectroscopic data from [10].

system. We use the Rainbow RABBIT method to study both the spectral amplitude and phase of the emitted electron wave packet (EWP). The influence of the spectrometer resolution and finite duration of the probing infrared (IR) pulse is discussed. In the case of the sp2$^+$ resonance, we fully characterize the resonant EWP using Short Time Fourier Transforms (STFT) and Wigner time-frequency representations which, together with theoretical calculations, allow us to resolve the ionization dynamics, and in particular, to disentangle the contributions of the two ionization paths.

This paper is structured as follows. In section 2, we present the experimental setup and methods used. Section 3 discusses the limitations to our measurements. In section 4, the results are presented and compared to theoretical calculations. Finally, section 5 is devoted to the representation of the autoionization dynamics in the time-frequency domain.

2. Methods

2.1. Experimental setup

The experiments were performed with a 1 kHz titanium sapphire laser producing pulses centered at 800 nm with a spectral width of 100 nm and a pulse duration around 20 fs. A dazzler was used to shape the pulse spectrum, allowing for the tuning of the central frequency from 790 nm to 810 nm with a reduced bandwidth of 70 nm. The pulses were sent to a spatially- and temporally-stabilized Mach-Zender interferometer [29] where the pulses were split in two arms. In the first arm they were focused with an on-axis spherical mirror ($f = 50$ cm focal length) in a 10-mm long gas cell filled with neon to generate high-order harmonics reaching energies in the extreme ultra-violet (XUV) up to 110 eV. A 200-nm thick aluminium foil was placed after the generating medium to filter out the remaining IR as well as the harmonics above 70 eV. The tunability of the laser source allowed us to choose particular harmonics to excite different autoionizing states, here the sp2$^+$ or the sp3$^+$ Fano resonances in helium located 60.15 and 63.66 eV from the ground state, respectively (table 1). In the second arm, a $\lambda/2$ wave plate and a broad-band polarizer were used to control the intensity of the probe beam which was delayed from the generated XUV pulse train with a piezoelectric stage. Both arms were then recombined and focused with a toroidal mirror ($f = 30$ cm) in a helium gas jet where they were spatially and temporally overlapped. The photoelectron spectrum resulting from the interaction of the two pulses with the helium atoms was measured with a 2-meter-long Magnetic Bottle Electron Spectrometer (MBES) which combines 4π sr collection efficiency with sub-100 meV resolution for electrons with low kinetic energy (below 10 eV). A retarding potential was applied to shift the photoelectron spectrum in this energy region.

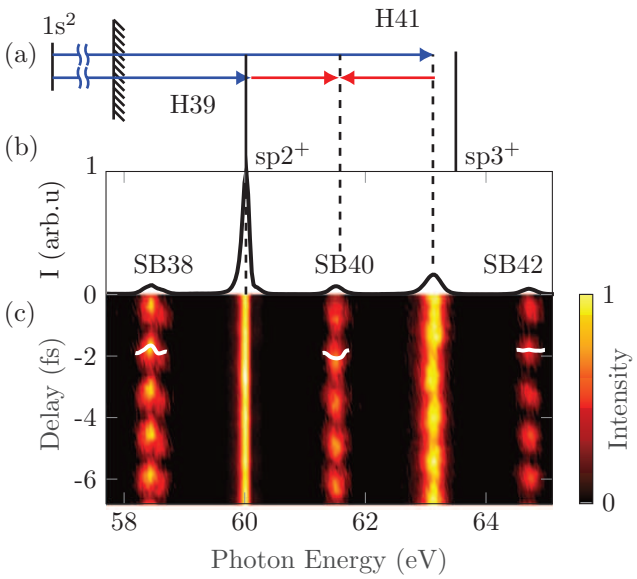

Figure 1. (a) Energy diagram and transitions when harmonic 39 is resonant with the sp2$^+$ state. The blue arrows correspond to the ionization from the ground state (1s^2) by the different harmonics, while the red arrows show the IR transitions used to couple the consecutive harmonics and giving rise to the sidebands. (b) Normalized intensity of the delay-integrated photoelectron spectrum showing the signature of the sp2$^+$ resonance in harmonic 39. (c) Photoelectron spectra taken as a function of the relative delay between the XUV pulse-train and the IR pulse. The intensity of the sidebands has been multiplied by 7 and the intensity of H41 by 5 for the sake of visibility. The intensity of the delay scan has been normalized to the maximum intensity of the whole scan. The Fano phase is imprinted in the phase of the neighboring sidebands 38 and 40, as shown by the white lines while the nonresonant sideband (SB42) has a flat phase. In this case, harmonic 41 is not resonant with the sp3$^+$ state, leading to sideband 42 being unaffected.

2.2. RABBIT method

Figure 1(b) shows a section of the delay-integrated photoelectron spectrum which is composed of a set of intense peaks (H39, H41) spaced by $2\hbar\omega_0$, where ω_0 is the central frequency of the IR field, resulting from the photoionization of the atoms by the harmonic comb. In the presence of the weak IR field, two-photon transitions (XUV±IR) can occur, as illustrated