1. Introduction

Upon the absorption of a sufficiently high energy photon, an electron in a bound system can be ionized. The escaping electron may interact with the remaining electrons leading to various processes such as shake-up [1, 2], double ionization [3] or Auger decay [4]. Another ionization mechanism induced by electron-electron interaction is autoionization, which results from excitation to a quasi-bound state which decays to the continuum. Autoionization, theoretically described in a seminal article by U. Fano [5], is a quantum interference effect between the direct path to the continuum and the resonant path through the quasi-bound state. The interference leads to the famous asymmetric Fano profile, characterized by a transition amplitude given by

$$R(\epsilon, q) = \frac{q+\epsilon}{\epsilon+i}, \tag{1}$$

where ϵ is the reduced energy $\epsilon = 2(E - E_\Phi)/\Gamma$ with E_Φ being the energy of the quasi-bound state and Γ its width, and q is the asymmetry parameter, proportional to the ratio between the direct and resonant transition amplitudes.

A textbook example of simple systems exhibiting electron correlation is the $^1P^o$ series of doubly excited states in He converging to the $n = 2$ state of He^+. Their observation by Madden and Codling [6] in 1963 indicated the breakdown of the independent electron picture, leading to strong theoretical activity to understand correlated two-electron dynamics (see e.g. [7] for a review). Experimentally, high resolution spectroscopic studies at synchrotron facilities have led to the determination of accurate spectroscopic parameters of a few Rydberg series [8, 9, 10]. More recently, with the increasing quality of experimental techniques, intriguing aspects often overlooked have been discussed such as the competition between autoionization and fluorescence decays [11], the role of relativistic effects [12], and possible mechanism for double excitation [13]. In the following, we focus on the lowest autoionizing states, denoted $sp2^+$ and $sp3^+$ (based on Cooper's classification[14]). Their energy, asymmetry parameter, linewidth and lifetime $\tau = \hbar/\Gamma$ are summarized in table 1.

Recently, thanks to the development of attosecond science, the ultrashort lifetime of autoionizing states could be measured in real time with pump-probe methods. Using the attosecond streaking technique [15, 16], the lifetime of the $sp2^+$ resonance in helium was determined [17]. An autoionizing decay of 8 fs was measured in Ar [18] using attosecond transient absorption. These two results were found in very good agreement with spectroscopic data. However, the lifetime is not sufficient to describe the entire autoionization dynamics, in particular the interferences between the direct and resonant ionization paths that are responsible for the asymmetric Fano lineshape. These interferences were not observed in the above experiments, probably because they occur shortly after the initial excitation, and were smoothed out by the 8-fs infrared probe beam.

A spectral approach provides an alternative to direct measurements in the time domain. The information on the autoionization dynamics, encoded in the complex spectral transition amplitude [Eq. 1], requires the measurement of its amplitude $|R(\epsilon, q)|$ and phase:

$$\arg\left[R(\epsilon, q)\right] = \arctan\epsilon - \pi\Theta(\epsilon + q) + \frac{\pi}{2} \tag{2}$$

where Θ is the Heaviside function. Spectral phase measurements can be performed by combining a comb of high harmonics (a train of attosecond pulses in the time domain) and a weak ($\approx 10^{11}$ W/cm^2) IR probe, with the so-called RABBIT technique (Reconstruction of Attosecond Beating by Interference of Two-photon Transitions) [19]. This method (together with its generalized FROG-CRAB version [20]) has allowed observing the signature of phase distortions induced by autoionizing resonances [21, 22, 23]. Recently, the spectral phase variation induced by an autoionizing resonance in argon was measured by scanning the harmonic frequency across the resonance and recording RABBIT traces for each frequency [24]. Using a spectrally-resolved technique, which we refer to as Rainbow RABBIT, Gruson and coworkers fully characterized the electron wave packet emitted through the $sp2^+$ autoionizing state in helium and could thus reconstruct the build-up of the resonance profile in the time domain [25]. Similar buildup was obtained by transient absorption spectroscopy [26] using an intense (10^{13} W/cm^2) probe pulse providing a fast gate. Control of the Fano profile was also demonstrated by varying the intensity of this probe pulse [27, 28].

Here, we characterize electronic wave packets emitted in He in the vicinity of the $sp2^+$ or $sp3^+$ doubly excited states, using a tunable titanium sapphire laser