Attosecond photoionization dynamics in the vicinity of the Cooper minima in argon
C. Alexandridi, D. Platzer, L. Barreau, D. Busto, S. Zhong, M. Turconi, L. Neoričić, H. Laurell, C. Arnold, A. Borot, et al.

To cite this version:
C. Alexandridi, D. Platzer, L. Barreau, D. Busto, S. Zhong, et al.. Attosecond photoionization dynamics in the vicinity of the Cooper minima in argon. Physical Review Research, American Physical Society, 2021, 3, pp.L012012. 10.1103/PhysRevResearch.3.L012012. cea-03439614

HAL Id: cea-03439614
https://hal-cea.archives-ouvertes.fr/cea-03439614
Submitted on 22 Nov 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons Attribution 4.0 International License
Attosecond photoionization dynamics in the vicinity of the Cooper minima in argon

C. Alexandridi,1,* D. Platzer,1* L. Barreau1, D. Busto2, S. Zhong2, M. Turconi,1 L. Neoriˇci´c1, M. Gisselbrecht2, E. Lindroth2, H. Laurell3, A. L’Huillier2, J. M. Dahlström2, and P. Salières1

1Université Paris-Saclay, CEA, CNRS, LIDYL, 91911 Gif-sur-Yvette, France
2Department of Physics, Lund University, Box 118, SE-22100 Lund, Sweden
3Department of Physics, Stockholm University, AlbaNova University Center, SE-10691 Stockholm, Sweden

(Received 29 July 2020; accepted 22 December 2020; published 5 February 2021)

Using a spectrally resolved electron interferometry technique, we measure photoionization time delays between the 3s and 3p subshells of argon over a large 34-eV energy range covering the Cooper minima in both subshells. The observed strong variations of the 3s – 3p delay difference, including a sign change, are well reproduced by theoretical calculations using the two-photon two-color random-phase approximation with exchange. Strong shake-up channels lead to photoelectrons spectrally overlapping with those emitted from the 3s subshell. These channels need to be included in our analysis to reproduce the experimental data. Our measurements provide a benchmark for multielectronic theoretical models aiming at an accurate description of interchannel correlation.

DOI: 10.1103/PhysRevResearch.3.L012012

Half a century after their theoretical description by Eisenbud [1], Wigner [2], and Smith [3], scattering delays—also called Wigner delays—can now be measured using attosecond spectroscopy, which allows for detailed studies of the correlated interactions within various quantum systems. In practice, this is done by recording the spectral variation of the quantum phase of electron wave packets photoemitted from solids [4,5], molecules [6–9], or atoms [10–21]. Of particular interest in scattering physics are spectral structures in the continua of atoms and molecules such as autoionizing resonances [22,23], shape resonances [24], and Cooper minima [25], as they carry detailed information on the internal structure, electronic correlations, potential, and orbital shapes. The rapidly varying phase in the vicinity of these structures has recently been investigated, e.g., for autoionizing [26–30] and shape resonances [7]. As for Cooper minima (CM), very few measurements have been performed, either in photoionization [14] or photorecombination [31,32] spectroscopy.

Ionization of argon from the n = 3 shell has attracted considerable attention due to abundant signatures of intra- and interorbital electronic correlations. In the case of the 3p subshell, intraorbital correlation is important close to the ionization threshold, due to the so-called ground-state correlation [33]. At higher photon energies, where the photoionization process can be described using single active electron models, the sign change in the 3p → sδ radial transition matrix element leads to a CM close to 53 eV [25,34]. As for the 3s subshell, interorbital correlation is important, since the 3p → sδ process is strongly coupled to 3s → ep [35]. This leads to a correlation-induced “replica” of the 3p CM in the 3s ionization channel, close to 42-eV photon energy, as shown in Fig. 1 [36].

All these correlation effects are expected to leave an imprint on the scattering and photoionization delays between the 3s and 3p electrons, which motivated a large number of calculations during the past decade in the demanding region above the 3s threshold [11,12,37–45]. The methods qualitatively agree on the behavior of the 3p atomic delays, which are slightly negative over a large energy region around the 3p CM. However, for the 3s case, the atomic delays close to the 3s CM strongly differ in magnitude and in sign depending on the degree of correlation included [39,44]. Up to now, two experiments using the RABBIT (reconstruction of attosecond beating by interference of two-photon transitions) technique have aimed at measuring the photoionization time-delay difference in the n = 3 shell of argon [11,12]. Unfortunately, for experimental reasons, the results were limited to the 34- to 40-eV photon energy range, below the 3s and 3p CM, preventing a detailed comparison over the entire spectral region.

In this Letter, we measure photoionization time delays between the 3s and 3p subshells of argon over a large energy range (34–68 eV) covering the CM in both subshells. The presence of multiple ionization channels leads to spectral congestion, which is one of the main experimental challenges. The spectrally resolved interferometric Rainbow RABBIT technique [27,28] allows us to substantially overcome this difficulty. The experimental results show strong variations of the 3s – 3p delay difference, with a change of sign in the 3s CM region. They are compared to theoretical calculations using the two-photon two-color random-phase approximation with exchange (2P2C-RPAE) method [44]. The agreement is excellent in—and above—the 3p CM region (45–68 eV) and

*These authors contributed equally to this work.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.

unsatisfactory in the 3s CM region (34–45 eV). We show that the presence of electrons from strong shake-up (SU) channels overlapping with 3s electrons is the likely reason for this deviation. By taking into account the dominant SU contribution, a good agreement between theory and experiment can be obtained in the 34- to 39-eV range.

The experiments were performed independently at the AT-TOLab facility in Saclay, France, and at Lund University, Sweden. The details of the two setups are described in the Supplemental Material [46]. Briefly, intense infrared (IR) femtosecond pulses are split in a Mach-Zehnder interferometer. In one arm of the interferometer, high-order harmonics are generated in neon gas and spectrally filtered by metallic foils. In the other arm, a small fraction of the IR radiation is temporally delayed. Both beams are recombined and then focused into an argon gas jet. The emitted electrons are detected with a 2-m-long magnetic bottle electron spectrometer (MBES).

To measure the photoionization time delays, we used the Rainbow RABBIT technique [27] which is schematically illustrated in Fig. 2(a). A comb of coherent harmonics ionizes argon atoms, creating one-photon electron wave packets (EWP) from both 3s and 3p subshells. The corresponding electron peaks are referred to as “3s or 3p harmonics” in the following. By adding the weak IR dressing field \((-10^{11} \text{ W/cm}^2)\), replicas of the initial EWPs are created by two-photon XUV ± IR transitions to the same final states. Their interference gives rise to the so-called sidebands (SB), the intensity of which oscillates as a function of the delay \(\tau\) between the XUV and IR pulses as

\[
SB_{n,i}(\tau) = A_{n,i} + B_{n,i} \cos \left[ 2 \omega_{00} \tau - \Delta \phi_{n}^{\text{XUV}} - \Delta \phi_{n,i}^{\text{A}} \right],
\]

where \(i\) is the ionization channel (3s, 3p, etc.), \(\omega_{00}\) is the angular frequency of the driving laser, \(\Delta \phi_{n}^{\text{XUV}} = \phi_{n+1} - \phi_{n-1}\) is the phase difference between two consecutive harmonics with orders \(n \pm 1\) [49], and \(\Delta \phi_{n,i}^{\text{A}}\) is the phase difference between the two-photon transition dipole matrix elements. In the so-called asymptotic approximation [50], \(\Delta \phi_{n,i}^{\text{A}}\) can be expressed as the sum of two contributions, \(\Delta \eta_{n,i} + \Delta \phi_{n,i}^{\text{cc}}\), where \(\Delta \eta_{n,k,i}\) is the scattering phase accumulated by the EWP in the one-photon (XUV) transition, which is intrinsic to the target atom, and \(\Delta \phi_{n,k,i}^{\text{cc}}\) is a quasuniversal measurement-induced phase shift due to the electron being probed by the IR laser field in a long-range potential with a Coulomb tail [50].

Group delays can be defined through \(\tau \approx \Delta \phi/2\omega_{00}\). The measured delay can be expressed as \(\tau_{n,i}^{\text{XUV}} + \tau_{n,i}^{\text{A}}\). Introducing the Wigner delay, \(\tau_{n,i}^{\text{W}} \approx \Delta \eta_{n,i}/2\omega_{00}\) and \(\tau_{n,i}^{\text{A}} \approx \tau_{n,i}^{\text{W}} + \tau_{n,i}^{\text{cc}}\). Since the 3s and 3p photoelectrons are ionized by the same harmonic comb, the \(\tau_{n,i}^{\text{XUV}}\) contribution of the ionizing radiation can be removed by calculating the difference of the delays for the two channels, giving direct access to \(\tau_{n,i}^{\text{A}}\) with high accuracy.
Two main experimental difficulties have prevented the measurement of this delay difference over the whole CM region. The first is that the ionization cross section is much weaker for 3s than for 3p, as shown in Fig. 1. The second is the spectral overlap of the two channels: the 3s sidebands $SB_{3s,3s}$ fall only 0.47 eV from the much more intense 3p harmonics $H_{3p-3p}$ due to the difference in ionization energies $\Delta E_{3s-3p} = 13.48$ eV $= 9\hbar \omega_0 - 0.47$ eV. To cope with these difficulties, previous studies [11, 12] spectrally isolated the two contributions by photoionizing with only four harmonics $(H_{21}-H_{27})$, selected by using a combination of filters and generation in argon. The main drawback of this approach is that it constrains the usable energy range to a 10-eV window below 40 eV.

In the present work, harmonics generated in neon were used as the ionizing radiation. Neon has a generation efficiency smaller than that of argon, but exhibits a quite flat harmonic spectrum with a much higher cutoff energy. In combination with a single 200-nm-thick Al filter, a broad spectrum (20–72 eV) including harmonics $H_{20-3p}$ is obtained. Under these conditions, the 3p harmonics overshadow the 3s sidebands. In Fig. 2(a), the contributions of the 3s SBs (harmonics) in the XUV + IR spectrum appear as small shoulders highlighted on the blue side of the 3p harmonics (SBs), as evidenced by the comparison with the XUV-only spectrum. In order to separate the two contributions, we perform a Rainbow RABBIT analysis of the recorded spectrogram; i.e., we analyze the $2\omega_0$ oscillations for each energy $E$ in the spectrum [see Eq. (1)]. The amplitude and the phase of these oscillations are shown in Figs. 2(b) and 2(c), respectively.

Between consecutive harmonics and sidebands of the same ionization channel, a dephasing of $\pm \pi$ is expected, as a result of the conservation of the total number of electrons [46]. Figure 2(c) shows multiple phase jumps, some of them close to $\pi$, others much less than $\pi$, which occur between sidebands (or harmonics) of different subshells. In addition to the high resolution of the MBES, the combination of amplitude and phase measurements allows us to distinguish the 3s contribution from the strong neighboring 3p electron peaks (see the dotted lines).

The measured $\tau_{3s}^A - \tau_{3p}^A$ delay differences are plotted in Fig. 3(a). The results reveal an interesting feature, namely, a change of sign around 43 eV. The negative sign in the low-energy region (close to the 3s threshold) is in part explained by the large negative delay contribution due to continuum-continuum transitions of slow photoelectrons [51]. However, in neon, the atomic delay difference between the 2s and 2p electrons stays negative up to high $\sim 100$-eV energies [19]. The positive sign in argon is thus a probable signature of the CM. Finally, the delay difference converges towards zero for higher energies where the 3s and 3p cross sections are unstructured.

The low-energy region is a particularly difficult range for the measurements because of the very weak signal of the 3s channel due to the CM, resulting in more than 3 orders of magnitude difference with the 3p channel [see Fig. 1(a)]). An extended analysis over a larger set of data was thus performed to improve the statistical significance of the result in the 34- to 43-eV spectral range corresponding to orders 22 to 27. There, the phases were extracted for both sideband and harmonic peaks. As discussed in Fig. 2(b), the harmonic phases are shifted by $\sim \pi$ relative to the SBs. However, this $\pi$ phase shift cancels when we calculate the delay difference between 3s and 3p harmonics. As shown in Fig. 3(a), the harmonic delays behave as an average of the neighboring sideband delays [46], with the only exception being $H_{27}$ at 42 eV.

In Fig. 3, the experimental results are compared with theoretical predictions using the recently developed 2P2C-RPAE method [44]. It consists of calculating complete self-consistent two-photon processes, including electron correlation in bound-continuum and continuum-continuum transitions, ion polarization effects, and the reversed photon time orders. The orbital energies of 3p and 3s are adjusted to fit the experimental ionization thresholds and the interaction with the fields is computed in the length gauge. The calculated $\tau_{3p}^A$ and $\tau_{3s}^A$ include the contribution from all emission angles, which corresponds to our experimental configurations. For $\tau_{3s}^A$, this integration significantly modifies the delays as compared to that in the XUV polarization direction [14, 39], while for $\tau_{3p}^A$, little effect is observed due to the single $3s \rightarrow 3p$ transition. Earlier work [39] shows that the full one-photon RPAE theory yields a 3s CM at 40 eV, while the restricted one-photon RPAE

FIG. 3. Atomic delay difference between 3s and 3p ionization channels in the vicinity of the 3s CM and 3p CM (highlighted in red/medium gray and blue/dark gray, respectively). (a) Experimental data from Lund (magenta/dark gray dots) and Saclay (orange/light gray markers, circles for sidebands, squares for harmonics) compared with simulations using the 2P2C-RPAE model (green/dark gray line). (b) Decomposition of the simulated delay-difference curve (green/dark gray line) into the 3s (red/blue dashed line) and 3p (blue/black dashed line) delay curves.
In this 3 additional ionic channels that perturb the measurements. SU channels associated with the 3 incoherent sum of the two signals, add incoherently in this angular-integrated measurement [52]. The incoherent sum of the two signals, H_{n+5.4p} overlapping with the difference in ion excitation energies being five times the laser photon energy, \Delta E_{4p-3s} = 7.90 eV \approx 5\hbar\omega_0. Similarly, the 3d channel has SB_{n+6.3d} overlapping with \Delta E_{3d-3s} = 9.34 eV \approx 6\hbar\omega_0.

We first consider the 34- to 39-eV range, where 3s and 4p are the dominant channels. We model the RABBIT modulation amplitude for a given channel by assuming that it is proportional to the one-photon cross section at a given final kinetic energy of the photoelectron [46]. This allows us to make simple estimates of the modulation strengths B_n. In Eq. (1) assuming constant harmonic photon flux [see Fig. 4(a)]. The crossing between the 3s and 4p modulation strengths close to 39 eV results in a significant SU contamination of the 3s time-delay measurements in this energy range.

Due to their different symmetries, the 3s and 4p channels add incoherently in this angular-integrated measurement [52]. The incoherent sum of the two signals, SB_{n+3s}, and H_{n+5.4p}, then results in a phase-shifted and amplitude-modified oscillating function, B_t = \cos(2\omega_0\tau - \theta_t), where

\[ \theta_t = \tan^{-1} \left( \frac{\sin(\delta_n)}{B_{n,3s}/B_{n+5.4p} + \cos(\delta_n)} \right) + \theta_{n,3s}, \]

\[ B_t = \sqrt{(B_{n+5.4p})^2 + (B_{n,3s})^2 + 2B_{n+5.4p}B_{n,3s}\cos(\delta_n)}, \]

with \theta_{n,3s} = \Delta\phi_{n,3s}^{\text{XLV}} + \Delta\phi_{n,3s}^{\text{SU}}. The relative phase between the 4p and 3s oscillations, \delta_n, is defined by

\[ \delta_n = \Delta\phi_{n+5.4p}^{\text{XLV}} - \Delta\phi_{n}^{\text{XLV}} + \Delta\phi_{n+5.4p}^{\text{SU}} - \Delta\phi_{n,3s}^{\text{SU}} + \pi, \]

where the \pi factor accounts for the opposite oscillations of H_{n+5.4p} with respect to the neighboring 4p sidebands [46]. \Delta\phi_{n+5.4p}^{\text{SU}} - \Delta\phi_{n}^{\text{SU}} \approx 0.14 \pi is determined by an independent measurement of the attosecond chirp. The 3s atomic phase is computed using the 2P2C-RPAE theory restricted to n = 3 correlation, while the 4p atomic phase is computed using the asymptotic approximation, as described in Ref. [46].

The resulting atomic delay for 4p SU, shown in Fig. 4(b), is found to be small, due to cancellation of the positive \Delta\phi_{n+5.4p}^{\text{SU}} and negative \Delta\phi_{n+5.4p}^{\text{SU}} contributions. This implies that the atomic phase \Delta\phi_{n+5.4p}^{\text{SU}} plays a negligible role in Eq. (3). Similarly \Delta\phi_{n,3s}^{\text{SU}}, as shown in Fig. 3(b), is small so that \delta_n is close but larger than \pi.

In the 34- to 38.5-eV range where B_{n+5.4p} \ll B_{n,3s}, \theta_t \approx (\pi - \delta_n)B_{n+5.4p}/B_{n,3s} + \theta_{n,3s}. The contribution of the 4p SU channel shifts down the effective atomic delay, in excellent agreement with the experimental results in Fig. 4(b). Around 39 eV, the similar amplitudes and \approx\pi-shifted oscillations of the two channels result in a minimum of the total modulation strength B_t and a fast variation of the effective delay as illustrated in Fig. 4 by the black lines. However, the 3d SU channel cannot be neglected anymore in this energy range. This SU process is much more complicated to estimate because it originates from the highly correlated 3s channel and exhibits a Cooper-like minimum as shown in Figs. 1(a) and 4(a). The 39- to 42-eV range is thus a transition region where at least three dephased incoherent channels contribute. This might explain why the delay measured at harmonic 27 (close to 42 eV) cannot be easily reproduced by modeling.

In conclusion, we have demonstrated the potential of the Rainbow RABBIT method to separate the contributions of the 3s and 3p ionization channels in argon and to measure the corresponding atomic delays for a wide range of energies (34–68 eV) that include both 3s and 3p Cooper minima. Our results are in excellent agreement with the predictions of many-body perturbation theory in a 24-eV range around the 3p Cooper minimum, revealing the high accuracy of both experiment and theory in this region. Furthermore, we identify two strong shake-up ionization channels, the contributions of...
which are probably responsible for the discrepancy observed in the 3s Cooper minimum region. This calls for further investigations to clarify their role. For instance, using a mid-IR driving wavelength from an optical parametric amplifier would allow for better sampling and tunability in order to separate the 3s, 3p, and shake-up channels. This study thus provides a step towards improving our understanding of the complex nature of correlated multielectron ionization dynamics.

This research was supported by Agence Nationale de la Recherche, Grants No. ANR-15-CE30-0001-CIMBAAD, No. ANR-11-EQPX0005-ATTOLAB, No. ANR-10-LABX-0039-PALM; COST, Grant No. CA18222-AttoChem and Laserlab-Europe, Grant No. EU-H2020-654148. The authors affiliated in Sweden acknowledge support from the Swedish Research Council (Grants No. 2018-03845, No. 2013-08185, and No. 2016-03789) and the Knut and Alice Wallenberg Foundation (Grant No. 2017.0104). J.M.D. acknowledges support from the Swedish Foundation’s Starting Grant by the Olle Engkvist’s Foundation. The Lund group thanks Raimund Feifel and Richard J. Squibb, Gothenburg University, for lending their magnetic bottle electron spectrometer.

[1] L. Eisenbud, The formal properties of nuclear collisions, Ph.D. thesis, Princeton University, 1948.
[2] E. P. Wigner, Lower limit for the energy derivative of the scattering phase shift, Phys. Rev. 98, 145 (1955).
[3] F. T. Smith, Lifetime matrix in collision theory, Phys. Rev. 118, 349 (1960).
[4] A. L. Cavalieri, N. Müller, T. Uphues, V. S. Yakovlev, A. Baltuška, B. Horvath, B. Schmidt, L. Blümel, R. Holzwarth, S. Hendel, M. Drescher, U. Kleineberg, P. M. Echenique, R. Kienberger, F. Krausz, and U. Heinzmann, Attosecond spectroscopy in condensed matter, Nature (London) 449, 1029 (2007).
[5] M. Ossiander, J. Riemschmieder, S. Nepple, M. Mittermaier, M. Schäffer, A. Duensing, M. S. Wagner, R. Heider, M. Wurzer, M. Gerl, M. Schnitzbaumer, J. V. Barth, F. Libisch, C. Lemell, J. Burgdörfer, P. Feulner, and R. Kienberger, Absolute timing of the photoelectric effect, Nature (London) 561, 374 (2018).
[6] S. Haessler, B. Fabre, J. Huguet, J. Caillat, T. Ruchon, P. Breger, B. Carré, E. Constant, A. Maquet, E. Mével, P. Salières, R. Taïeb, and Y. Mairesse, Phase-resolved attosecond near-threshold photoionization of molecular nitrogen, Phys. Rev. A 80, 011404(R) (2009).
[7] M. Huppert, I. Jordan, D. Baykusheva, A. von Conta, and H. J. Wörner, Attosecond Delays in Molecular Photoionization, Phys. Rev. Lett. 117, 093001 (2016).
[8] S. Beaulieu, A. Comby, A. Clergerie, J. Caillat, D. Descamps, N. Dudovich, B. Fabre, R. Géneaux, F. Légaré, S. Petit, B. Pons, G. Porat, T. Ruchon, R. Taïeb, V. Blanchet, and Y. Mairesse, Attosecond-resolved photoionization of chiral molecules, Science 358, 1288 (2017).
[9] J. Vos, L. Cattaneo, S. Patchkovskii, T. Zimmermann, C. Cirelli, M. Lucchini, A. Kheifets, A. S. Landsman, and U. Keller, Orientation-dependent stereo Wigner time delay and electron localization in a small molecule, Science 360, 1326 (2018).
[10] M. Schultz, M. Fieß, N. Karpowicz, J. Gagnon, M. Korban, M. Hofstetter, S. Nepple, A. L. Cavalieri, Y. Komninos, Th. Mercouris, C. A. Nicolaides, R. Pazourek, S. Nagele, J. Feist, J. Burgdörfer, A. M. Azzeer, R. Ersstorfer, R. Kienberger, U. Kleineberg, E. Goulielmakis et al., Delay in photoionization, Science 328, 1658 (2010).
[11] K. Klünder, J. M. Dahlström, M. Gisselbrecht, T. Fordell, M. Swoboda, D. Guénot, P. Johnsson, J. Caillat, J. Mauritsson, A. Maquet, R. Taïeb, and A. L’Huillier, Probing Single-Photon Ionization on the Attosecond Time Scale, Phys. Rev. Lett. 106, 143002 (2011).
[12] D. Guénot, K. Klünder, C. L. Arnold, D. Kroon, J. M. Dahlström, M. Miranda, T. Fordell, M. Gisselbrecht, P. Johnsson, J. Mauritsson, E. Lindroth, A. Maquet, R. Taïeb, A. L’Huillier, and A. S. Kheifets, Photoionization-time-delay measurements and calculations close to the 3s-ionization-cross-section minimum in Ar, Phys. Rev. A 85, 053424 (2012).
[13] D. Guénot, D. Kroon, E. Balogh, E. W. Larsen, M. Kotur, M. Miranda, T. Fordell, P. Johnsson, J. Mauritsson, M. Gisselbrecht, K. Varju, C. L. Arnold, T. Carette, A. S. Kheifets, E. Lindroth, A. L’Huillier, and J. M. Dahlström, Measurements of relative photoemission time delays in noble gas atoms, J. Phys. B: At., Mol. Opt. Phys. 47, 245602 (2014).
[14] C. Palatchi, J. M. Dahlström, A. S. Kheifets, I. A. Ivanov, D. M. Canaday, P. Agostini, and L. F. DiMauro, Atomic delay in helium, neon, argon and krypton, J. Phys. B: At., Mol. Opt. Phys. 47, 245003 (2014).
[15] M. Sabbar, S. Heuser, R. Boge, M. Lucchini, T. Carette, E. Lindroth, L. Gallmann, C. Cirelli, and U. Keller, Resonance Effects in Photoemission Time Delays, Phys. Rev. Lett. 115, 133001 (2015).
[16] S. Heuser, Á. Jiménez Galán, C. Cirelli, C. Marante, M. Sabbar, R. Boge, M. Lucchini, L. Gallmann, I. Ivanov, A. S. Kheifets, J. M. Dahlström, E. Lindroth, L. Argenti, F. Martín, and U. Keller, Angular dependence of photoemission time delay in helium, Phys. Rev. A 94, 063409 (2016).
[17] I. Jordan, M. Huppert, S. Pabst, A. S. Kheifets, D. Baykusheva, and H. J. Wörner, Spin-orbit delays in photoemission, Phys. Rev. A 95, 013404 (2017).
[18] M. Ossiander, F. Siegrist, V. Shirvanyan, R. Pazourek, A. Sommer, T. Latka, A. Guggenmos, S. Nagele, J. Feist, J. Burgdörfer, R. Kienberger, and M. Schultz, Attosecond correlation dynamics, Nat. Phys. 13, 280 (2017).
[19] M. Isinger, R. J. Squibb, D. Busto, S. Zhong, A. Harth, D. Kroon, S. Nandi, C. L. Arnold, M. Miranda, J. M. Dahlström, E. Lindroth, R. Feifel, M. Gisselbrecht, and A. L’Huillier, Photoionization in the time and frequency domain, Science 358, 893 (2017).
[20] C. Cirelli, C. Marante, S. Heuser, C. L. M. Petersson, Á. Jiménez-Galán, L. Argenti, S. Zhong, D. Busto, M. Isinger, S. Nandi, S. Maclot, L. Rading, P. Johnsson, M. Gisselbrecht, M. Lucchini, L. Gallmann, J. M. Dahlström, E. Lindroth, A. L’Huillier, F. Martín, and U. Keller, Anisotropic photoemission time delays close to a Fano resonance, Nat. Commun. 9, 955 (2018).
[21] J. Joseph, F. Holzmeier, D. Bresteau, C. Spezzani, T. Ruchon, J.-F. Hergott, O. Tcherbakoff, P. D’Oliveira, J. C. Houwer, and D. Dowek, Angle-resolved studies of UV+IR two-photon ionization in the RABBITT scheme, J. Phys. B: At., Mol. Opt. Phys. 53, 184007 (2020).

[22] H. Beutler, Über absorptionsersionen von argon, krypton und xenon zu termen zwischen den beiden ionisierungsgrenzen $^2P_{3/2}$ und $^2P_{1/2}$, Z. Phys. 93, 177 (1935).

[23] U. Fano, Effects of configuration interaction on intensities and phase shifts, Phys. Rev. 124, 1866 (1961).

[24] J. L. Dehmer, Evidence of effective potential barriers in the x-ray absorption spectra of molecules, J. Chem. Phys. 56, 4496 (1972).

[25] J. W. Cooper, Photoionization from outer atomic subshells. A model study, Phys. Rev. 128, 681 (1962).

[26] M. Kotur, D. Guénot, Á. Jiménez-Galán, D. Kroon, E. W. Larsen, M. Louisy, S. Bengtsson, M. Miranda, J. Mauritsson, C. L. Arnold, S. E. Cantor, M. Gisselbrecht, T. Carette, J. M. Dahlström, E. Lindroth, A. Maquet, L. Argenti, F. Martín, and A. L’Huillier, Spectral phase measurement of a Fano resonance using tunable attosecond pulses, Nat. Commun. 7, 10566 (2016).

[27] V. Gruson, L. Barreau, Á. Jiménez-Galan, F. Risoud, J. Caillat, A. Maquet, B. Carré, F. Lepetit, J.-F. Hergott, T. Ruchon, L. Argenti, R. Taiéb, F. Martín, and P. Salières, Attosecond dynamics through a Fano resonance: Monitoring the birth of a photoelectron, Science 354, 734 (2016).

[28] D. Busto, L. Barreau, M. Isinger, M. Turconi, C. Alexandridi, A. Harth, S. Zhong, R. J. Squibb, D. Kroon, S. Plogmaker, M. Miranda, A. Jiménez-Galán, L. Argenti, C. L. Arnold, R. Feifei, F. Martín, M. Gisselbrecht, A. L’Huillier, and P. Salières, Time–frequency representation of autoionization dynamics in helium, J. Phys. B: At., Mol. Opt. Phys. 51, 044002 (2018).

[29] L. Barreau, C. L. M. Petersson, M. Klinker, A. Camper, C. Marante, T. Gorman, D. Kiesewetter, L. Argenti, P. Agostini, J. González-Vázquez, P. Salières, L. F. DiMauro, and F. Martín, Disentangling Spectral Phases of Interfering Autoionizing States from Attosecond Interferometric Measurements, Phys. Rev. Lett. 122, 253203 (2019).

[30] M. Turconi, L. Barreau, D. Busto, M. Isinger, C. Alexandridi, A. Harth, R. J. Squibb, D. Kroon, C. L. Arnold, R. Feifei, M. Gisselbrecht, L. Argenti, F. Martín, A. L’Huillier, and P. Salières, Spin–orbit-resolved spectral phase measurements around a Fano resonance, J. Phys. B: At., Mol. Opt. Phys. 53, 184003 (2020).

[31] S. B. Schoun, R. Chirla, J. Wheeler, C. Roedig, P. Agostini, L. F. DiMauro, K. J. Schafer, and M. B. Gaarde, Attosecond Pulse Shaping Around a Cooper Minimum, Phys. Rev. Lett. 112, 153001 (2014).

[32] T. Scarborough, T. Gorman, F. Mauger, P. Sándor, S. Khatri, M. Gaarde, K. Schafer, P. Agostini, and L. F. DiMauro, Full characterization of a molecular Cooper minimum using high-harmonic spectroscopy, Appl. Sci. 8, 1129 (2018).

[33] A. F. Starace, Theory of atomic photoionization, in Handbuch der Physik, edited by W. Mehlhorn (Springer, Berlin, 1982), Vol. 31, p. 1.

[34] J. A. R. Samson and W. C. Stolte, Precision measurements of the total photoionization cross-sections of He, Ne, Ar, Kr, and Xe, J. Electron Spectrosc. Relat. Phenom. 123, 265 (2002).

[35] M. Y. Amusia, V. K. Ivanov, N. A. Cherepkov, and L. V. Chernysheva, Interference effects in photoionization of noble gas atoms outer s-subshells, Phys. Lett. A 40, 361 (1972).

[36] B. Möbus, B. Magel, K.-H. Schartner, B. Langer, U. Becker, M. Wildberger, and H. Schmoranzer, Measurements of absolute Ar 3s photoionization cross sections, Phys. Rev. A 47, 3888 (1993).

[37] A. S. Kheifets, Time delay in valence-shell photoionization of noble-gas atoms, Phys. Rev. A 87, 063404 (2013).

[38] J. M. Dahlström, T. Carette, and E. Lindroth, Diagrammatic approach to attosecond delays in photoionization, Phys. Rev. A 86, 061402(R) (2012).

[39] J. M. Dahlström and E. Lindroth, Study of attosecond delays using perturbation diagrams and exterior complex scaling, J. Phys. B: At., Mol. Opt. Phys. 47, 124012 (2014).

[40] M. Magrakvelidze, M. E.-A. Madjet, G. Dixit, M. Ivanov, and H. S. Chakraborty, Attosecond time delay in valence photoionization and photorecombination of argon: A time-dependent local-density-approximation study, Phys. Rev. A 91, 063415 (2015).

[41] L.-W. Pi and A. S. Landsman, Attosecond time delay in photoionization of noble-gas and halogen atoms, Appl. Sci. 8, 322 (2018).

[42] A. W. Bray, F. Naseem, and A. S. Kheifets, Simulation of angular-resolved RABBITT measurements in noble-gas atoms, Phys. Rev. A 97, 063404 (2018).

[43] S. A. Sato, H. Hübener, A. Rubio, and U. De Giovannini, First-principles simulations for attosecond photoelectron spectroscopy based on time-dependent density functional theory, Eur. Phys. J. B 91, 126 (2018).

[44] J. Vinbladh, J. M. Dahlström, and E. Lindroth, Many-body calculations of two-photon, two-color matrix elements for attosecond delays, Phys. Rev. A 100, 043424 (2019).

[45] A. S. Kheifets, D. Toffoli, and P. Declercq, Angular dependent time delay near correlation induced Cooper minima, J. Phys. B: At., Mol. Opt. Phys. 53, 115201 (2020).

[46] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevResearch.3.L012012 for details on the experimental and theoretical methods.

[47] W. Wijesundera and H. P. Kelly, Correlation satellites in the photoelectron spectrum of argon, Phys. Rev. A 39, 634 (1989).

[48] U. Becker, B. Langer, H. G. Kerkhoff, M. Kupsch, D. Szostak, R. Wehlitz, P. A. Heimann, S. H. Liu, D. W. Lindle, T. A. Ferrett, and D. A. Shirley, Observation of Many New Argon Valence Satellites Near Threshold, Phys. Rev. Lett. 60, 1490 (1988).

[49] Y. Mairesse, A. de Bohan, L. J. Frasinski, H. Mordj, L. C. Dinu, P. Monchicourt, P. Breger, M. Kovačev, R. Taiéb, B. Carré, H. G. Muller, P. Agostini, and P. Salières, Attosecond synchronization of high-harmonic soft x-rays, Science 302, 1540 (2003).

[50] J. M. Dahlström, D. Guénot, K. Klünder, M. Gisselbrecht, J. Mauritsson, A. L’Huillier, A. Maquet, and R. Taiéb, Theory of attosecond delays in laser-assisted photoionization, Chem. Phys. 414, 53 (2013).

[51] J. M. Dahlström, A. L’Huillier, and A. Maquet, Introduction to attosecond delays in photoionization, J. Phys. B: At., Mol. Opt. Phys. 45, 183001 (2012).

[52] C. Bourassin-Bouchet, L. Barreau, V. Gruson, J.-F. Hergott, F. Quéré, P. Salières, and T. Ruchon, Quantifying decoherence in Attosecond Metrology, Phys. Rev. X 10, 031048 (2020).