Experimental study of the laser-induced ionization of heavy metal and metalloid ions: Au\(^+\) and Si\(^{2+}\) in intense and sculpted femtosecond laser fields

Bo Ying\(^{1,2,3,}\), Frank Machalett\(^{1,2,3}\), Vanessa Huth\(^{1}\), Matthias Kübel\(^{1,2}\), A Max Sayler\(^{1,2,4}\), Thomas Stöhlker\(^{1,2,3}\), Gerhard G Paulus\(^{1,2,3,}\) and Philipp Wustelt\(^{1,2,}\)

1 Institute of Optics and Quantum Electronics, Friedrich Schiller University Jena, Max-Wien-Platz 1, 07743 Jena, Germany
2 Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena, Germany
3 GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany
E-mail: bo.ying@uni-jena.de, gerhard.paulus@uni-jena.de and philipp.wustelt@uni-jena.de

Received 6 June 2021, revised 12 August 2021
Accepted for publication 7 September 2021
Published 30 September 2021

Abstract

We implement a liquid metal ion source in a 3D coincidence momentum spectroscopy setup for studying the interaction of ionic targets with intense laser pulses. Laser intensities of up to \(4 \times 10^{16} \text{ W cm}^{-2}\) allow for the observation of up to ten-fold ionization of Au\(^+\)-ions and double ionization of Si\(^{2+}\)-ions. Further, by utilizing two-color sculpted laser fields to control the ionization process on the attosecond time scale, we demonstrate the capability to resolve the recoil ion momenta of heavy metal atoms. Simulations based on a semiclassical model assuming purely sequential ionization reproduce the experimental data well. This work opens up the use of a range of metallic and metalloid ions, which have hardly been investigated in strong-field laser physics so far.

Keywords: experimental, laser-induced ionization, liquid metal ion source, momentum spectroscopy, two-color-laser fields, metal and metalloid ions

(Some figures may appear in colour only in the online journal)

1. Introduction

The interaction of atoms and molecules with intense ultra-short laser pulses addresses several fundamental questions of light–matter interaction and challenges the understanding and modeling of many quantum phenomena [1–3]. The first effect that occurs in atoms exposed to strong fields is tunneling of one or several electrons [4–6]. Its highly nonlinear nature is at the root of a series of extensively studied phenomena in attosecond laser physics, in particular above-threshold ionization, high-order harmonic generation, and non-sequential double or multiple ionization (NSDI).

Since the advent of strong-field laser physics, the great majority of ionization experiments have been conducted utilizing conventional targets such as neutral atoms or molecules, often just rare gas atoms [7]. The reasons are mainly of technical nature, as these targets can easily be handled and fed into the interaction region by gas nozzles with high density and reproducibility. Ionic targets, on the other hand, enable the investigation of many interesting fundamental systems such as
He$^+$ and H$_2^+$ [8, 9], or exotic molecules that can only be produced in an ion source, e.g. H$_2$ [10] and HeH$^+$ [11, 12]. In addition, laser experiments with ions are also interesting for charged noble gases or other light atoms and molecules.

A large region of the periodic table, which so far has hardly been considered in strong-field laser physics, is represented by metals and metalloids. From a theoretical point of view, modeling such complex many-electron systems is a challenge [13], but gives access to light-driven dynamics in multi-electron systems. Specifically, the ionization of electrons from the f(fundamental)-shell is largely unexplored to date. Further, higher charge states of heavier targets may require the inclusion of relativistic effects in the theoretical description. Another central issue for understanding strong-field light–matter interactions is effects beyond the single-active-electron approximation or the dipole approximation [3].

In order to address these questions experimentally, an important requirement are highly differential data, i.e. the measurement of the momenta of the fragments—the photoelectrons and ions. Accordingly, recoil ion momentum spectroscopy plays an important role in the investigation of the different types of ionization dynamics and has provided important insights into the tunnel ionization process [14], sequential (SDI) [15] and NSDI dynamics [16], to mention just a few. Indeed, a number of such studies investigated signatures of multi-electron effects beyond NSDI, for example as a consequence of transient reorientation processes of the intermediate ionic charge states [6, 17–22] or due to a sub-cycle process [23].

Most of the momentum spectroscopy studies to date have been limited to single and double ionization (DI) [17, 18]. Indeed, for more than two ionization steps the measurement of all electron momenta is technically extremely challenging. Accordingly, for investigating multiple ionization, the information must be extracted from the photoions. Momentum resolved measurements went up to triple [24] and quadruple ionization [25].

Here, we report on the realization of recoil ion spectroscopy in strong-field ionization measurements of metal and metalloid ions, specifically the elements gold and silicon. From the technical point of view, these targets are only available as solids, such that the implementation of recoil momentum spectroscopy of laser-generated fragments is not obvious. We propose to use a liquid metal ion source (LMIS) and present first results. Two respective experiments will be presented. First, high laser intensities are employed in order to produce and detect highly charged ions. Second, we apply a two-color laser field in order to manipulate the recoil momenta with sub-cycle resolution.

2. Experiment

The LMIS is combined with an ion beam apparatus, which in turn is equipped with a 3D momentum spectrometer [8, 25]. For a proof-of-principle study, an emitter element from an electron beam source originally built for a historic scanning electron microscope (ZEISS model ZRM 20) is used in a simple and compact ion source setup [26]. A tungsten needle wetted with an alloy of AuSi in eutectic composition results in ion emission if the emitter is heated approximately 20–50 K above the eutectic temperature of 362 °C [27] and field strengths of $\approx 10^{10}$ V m$^{-1}$ [28] are applied. The surface of the liquid alloy forms in the electric field a so-called Taylor-cone. The tip radius of the Taylor-cone, which is in the low nm-dimension, enables these high field strengths, which are necessary for field evaporation and field ionization. Then the ions are extracted from the source and accelerated to $\approx$8 keV kinetic energy. With moderate source currents of $\approx$ 5 $\mu$A, stable and continuous operation can be achieved. Two einzel lenses and deflectors are used to pass the ion beam through a Wien filter ($E \times B$ velocity filter), which allows characterization of the ion spectrum emitted from the source.

The Wien filter is also used for target preparation, i.e. for the selection of a single ion species with a defined $q/m$ ratio. Further, a third einzel lens and adjustable apertures shape
an intensity of 3 corresponding instantaneous electric field of a 30 fs-laser pulse with both Au center wavelength of 1030 nm. The two-color laser fields are (activefibersystems) with 100 kHz pulse repetition rate and a low ion density. We use a commercial femtosecond fiber laser statistics, a high pulse repetition rate in face of the ondharmonic must be performed. In order to achieve sufficient with different relative phases between fundamental and sec-

tional gold ion Au$_{2+}$, which is also present in the ion beam as it cannot be separated from the Au$^{+}$-ions by the Wien filter. However, the aforementioned signal can be largely distin-
guished from the Au$_{2+}$ ions due to their different impact positions and TOF. The analysis of the laser-induced fragmentation of Au$_{2+}$ is not the subject of this paper but will be presented in another report.

The same measurement is repeated using a target of Si$_2^{2+}$. For silicon the doubly charged ion is chosen for the measure-

to distinguish different fragments by their detected position, weak static transverse electric fields before the detector are used. The position and time-of-flight (TOF) information for each ionized ion is detected. This allows for the reconstruction of the full 3D-momenta of all nuclear fragments [25].

3. Metallic and metalloid ions in intense laser fields

In a first measurement we employ the highest available laser intensities in order to investigate the formation of highly-charged metallic ions. Figure 1(b) shows the measured ion yield distribution at the detector plane. Two electrostatic deflectors behind the interaction point provide transverse fields which separate the laser induced ions according to their charge state, $Q$, in position, such that the events corresponding to the different charge states are arranged along a line from the center of the detector to the right up. We observe laser-induced charge states from Au$_{2+}$ up to Au$_{11+}$. The distribution has some background from the incident Au$^{+}$ beam, which partially misses the blocking FC. In addition, figure 1(b) contains events arising from the fragmentation of the doubly charged molecular gold ion Au$_{2+}$, which is also present in the ion beam as it cannot be separated from the Au$^{+}$-ions by the Wien filter. However, the aforementioned signal can be largely distin-
guished from the Au$_{2+}$ ions due to their different impact positions and TOF. The analysis of the laser-induced fragmentation of Au$_{2+}$ is not the subject of this paper but will be presented in another report.

The same measurement is repeated using a target of Si$_2^{2+}$. For silicon the doubly charged ion is chosen for the measure-

to distinguish different fragments by their detected position, weak static transverse electric fields before the detector are used. The position and time-of-flight (TOF) information for each ionized ion is detected. This allows for the reconstruction of the full 3D-momenta of all nuclear fragments [25].

3. Metallic and metalloid ions in intense laser fields

In a first measurement we employ the highest available laser intensities in order to investigate the formation of highly-charged metallic ions. Figure 1(b) shows the measured ion yield distribution at the detector plane. Two electrostatic deflectors behind the interaction point provide transverse fields which separate the laser induced ions according to their charge state, $Q$, in position, such that the events corresponding to the different charge states are arranged along a line from the center of the detector to the right up. We observe laser-induced charge states from Au$_{2+}$ up to Au$_{11+}$. The distribution has some background from the incident Au$^{+}$ beam, which partially misses the blocking FC. In addition, figure 1(b) contains events arising from the fragmentation of the doubly charged molecular gold ion Au$_{2+}$, which is also present in the ion beam as it cannot be separated from the Au$^{+}$-ions by the Wien filter. However, the aforementioned signal can be largely distin-
guished from the Au$_{2+}$ ions due to their different impact positions and TOF. The analysis of the laser-induced fragmentation of Au$_{2+}$ is not the subject of this paper but will be presented in another report.

The same measurement is repeated using a target of Si$_2^{2+}$. For silicon the doubly charged ion is chosen for the measure-

to distinguish different fragments by their detected position, weak static transverse electric fields before the detector are used. The position and time-of-flight (TOF) information for each ionized ion is detected. This allows for the reconstruction of the full 3D-momenta of all nuclear fragments [25].

3. Metallic and metalloid ions in intense laser fields

In a first measurement we employ the highest available laser intensities in order to investigate the formation of highly-charged metallic ions. Figure 1(b) shows the measured ion yield distribution at the detector plane. Two electrostatic deflectors behind the interaction point provide transverse fields which separate the laser induced ions according to their charge state, $Q$, in position, such that the events corresponding to the different charge states are arranged along a line from the center of the detector to the right up. We observe laser-induced charge states from Au$_{2+}$ up to Au$_{11+}$. The distribution has some background from the incident Au$^{+}$ beam, which partially misses the blocking FC. In addition, figure 1(b) contains events arising from the fragmentation of the doubly charged molecular gold ion Au$_{2+}$, which is also present in the ion beam as it cannot be separated from the Au$^{+}$-ions by the Wien filter. However, the aforementioned signal can be largely distin-
guished from the Au$_{2+}$ ions due to their different impact positions and TOF. The analysis of the laser-induced fragmentation of Au$_{2+}$ is not the subject of this paper but will be presented in another report.

The same measurement is repeated using a target of Si$_2^{2+}$. For silicon the doubly charged ion is chosen for the measure-

to distinguish different fragments by their detected position, weak static transverse electric fields before the detector are used. The position and time-of-flight (TOF) information for each ionized ion is detected. This allows for the reconstruction of the full 3D-momenta of all nuclear fragments [25].

3. Metallic and metalloid ions in intense laser fields

In a first measurement we employ the highest available laser intensities in order to investigate the formation of highly-charged metallic ions. Figure 1(b) shows the measured ion yield distribution at the detector plane. Two electrostatic deflectors behind the interaction point provide transverse fields which separate the laser induced ions according to their charge state, $Q$, in position, such that the events corresponding to the different charge states are arranged along a line from the center of the detector to the right up. We observe laser-induced charge states from Au$_{2+}$ up to Au$_{11+}$. The distribution has some background from the incident Au$^{+}$ beam, which partially misses the blocking FC. In addition, figure 1(b) contains events arising from the fragmentation of the doubly charged molecular gold ion Au$_{2+}$, which is also present in the ion beam as it cannot be separated from the Au$^{+}$-ions by the Wien filter. However, the aforementioned signal can be largely distin-
guished from the Au$_{2+}$ ions due to their different impact positions and TOF. The analysis of the laser-induced fragmentation of Au$_{2+}$ is not the subject of this paper but will be presented in another report.

The same measurement is repeated using a target of Si$_2^{2+}$. For silicon the doubly charged ion is chosen for the measure-

to distinguish different fragments by their detected position, weak static transverse electric fields before the detector are used. The position and time-of-flight (TOF) information for each ionized ion is detected. This allows for the reconstruction of the full 3D-momenta of all nuclear fragments [25].
of the Keldysh parameter (see figure 2(a)) for the different ionization steps indicates that nonadiabatic contributions can occur at least for the ionization of the lower charge states.

Thus, the ionization dynamics was modeled using the ionization rates proposed in [32]. Our model assumes purely sequential ionization. Therefore, interdependencies between subsequent ionization steps are solely introduced by the relative ionization times of different charge states, which are predicted by the field-governed ionization rates. The corresponding set of coupled rate equations read

\[ \frac{dN_Q}{dt} = -N_Q \Gamma_Q \]

\[ \frac{dN_{Q-1}}{dt} = -N_Q \Gamma_Q + N_{Q+1} \Gamma_{Q+1} \]

where \( N_Q \) is time-dependent population of charge state \( Q \) and \( \Gamma_Q \) denotes the ionization rate. Thus, any deviations from this purely sequential ionization dynamics could then be attributed to different aspects of multi-electron dynamics.

The simulated time-resolved population of the charge states in the laser pulse from the solution of the above rate equations is displayed in figure 2(b) and revealing a fast transition through subsequent charge states within a few femtoseconds. The ionization steps of \( \text{Au}^{11+} \) are distributed over the rising edge of the pulse, while for \( \text{Si}^{12+} \) the transition to \( \text{Si}^{13+} \) is saturated long before the peak intensity of the pulse is reached.

The simultaneous detection of all charge states (see figure 1) in a measurement with a single laser pulse is a consequence of the focal volume effect inherent in all interactions of extended targets with focused laser fields. Only the laser intensity in the middle of the focus is high enough to ionize \( \text{Au}^{11+} \) 10-times and thus can produce \( \text{Au}^{11+} \). Ions in volume elements further away from the center of the focus can only be ionized to correspondingly lower charge states and thus result in the series of lower charge states in the measured signal [33].

The intensity dependence of the multiple ionization of \( \text{Au}^{11+} \) is experimentally further investigated by a scan of the laser intensity in the measurement. This is achieved by performing a so-called \( z \)-scan, i.e. scanning the laser focal position across the ion beam [34]. The laser peak intensity was estimated by the focused laser spot size measured by a CCD camera.

The peak intensity- and charge state-dependent yield is shown in figure 3(a). We compare these results to predictions from semi-classical simulations based on the ionization rates described above. The results are shown in figure 3(b).
occurrence of different charge states of Au\(^+\) as a function of the intensity is well reproduced. For predicting the correct relative yield of all charge states in a single measurement, we include focal volume averaging by taking into account the evolution of the laser focal spot size and the extension of the ion beam (see figure 3(c)).

To achieve this, the simulations are repeated for an ensemble of field strengths, which results from the interaction of the ion beam with the three dimensional intensity distribution of the laser focus according to the experimental conditions [31, 34, 35]. As measured in the experiment, we assumed an ion beam size of 300 \(\mu\)m and a Rayleigh range \(z_R \approx 200 \mu\)m of the laser beam. The contribution of each field strength to the charge-state dependent yield is weighted with the corresponding ionization probability and the relative abundance of this intensity value in the Gaussian focus.

These results show that the measurement of different charge states provides a simple and quantitative measure of the laser intensity in the experiment.

In addition to the charge state-resolved yield, we can evaluate the momentum distribution, although it is complicated by several circumstances. First, for the ionization of the heavy atomic ions reported here, the momentum transfer resulting from the ionization is rather small as compared to the initial momentum distribution of the ions. This makes recoil momentum spectroscopy using heavy atoms very challenging. Second, since the source is not yet fully optimized, instabilities of the pointing of the ion beam are blurring the momentum distribution. Third, the analysis of the momentum distributions is limited by low statistics resulting from the low target density in combination with the low repetition rate of the laser.

Figure 4 shows the measured momentum distributions for Au\(^Q+\)-ions. Although the count rates for the higher charge states are poor, we can observe that the width of the momentum distribution is increasing with final charge state. We compare this observation to predictions from the ionization model as detailed in [31]. In short, based on the static field ionization rates [36] and the solution of the rate equations, ionization times are computed. Subsequently, assuming a single active electron in the field the asymptotic electron momenta, \(p_i = A(t_i)\) with \(i = 2 \ldots 11\), and the resulting momentum of
Figure 6. Simulated momentum distribution in laser polarization direction for ionization of Au$^+$ ions with a peak intensity of $2.5 \times 10^{14}$ W cm$^{-2}$ and a pulse duration of 40 fs in comparison to figure 5. (a) Relative phase-dependent momentum distribution $p_\parallel$ of Au$^{2+}$ produced by SI, (b) same as (a) for Au$^{3+}$ produced by DI, (c) and (d) the asymmetry map for SI and DI. (e) Mean of $p_\parallel$ of SI and DI as a function of the relative phase. (f) Phase dependent yield for SI and DI.

the multiple charged ion, $p_{\text{ion},Q} = -\sum_{i=2}^{Q} p_i$, is calculated, where $A(t)$ is the laser vector potential $A(t) = -\int_{-\infty}^{t} E(t') dt'$. Comparison between the measured and simulated spectra shows that the simulated distributions are considerably narrower than the measured ones. As already indicated, this can be explained by the fact that the measured momentum distributions are broadened by the initial momentum distribution of the ion beam and fluctuations of the beam pointing during the measurement. Nevertheless, the qualitative trend of increasing width with increasing charge state is clearly present and agrees with theory.

4. Metallic ions in tailored laser fields

For even more demanding proof-of-principle experiments with heavy ions, we performed phase-resolved two-color measurements with the Au$^+$-ion beam using a high-repetition rate laser system at 100 kHz. The 100-fold higher pulse repetition rate compensates the low event rate due to the low target density and shortens the measurement time, which helps managing the instabilities of the ion beam. The second harmonic of the two-color laser field is used to steer the momenta of the atomic fragments in a well-defined way. In fact, sub-cycle tuning of the instantaneous electric field provides a well-established and efficient technique to manipulate and control various processes in strong-field and attosecond physics [37–39]. To this end, the relative phase between a fundamental wave and its second harmonic is varied in order to modulate the yield as well as the momenta of the photo electrons and ions resulting from strong-field ionization.

Due to the lower pulse energy of the high-repetition rate laser system, the peak intensity in this experiment is considerably lower as compared to the measurement at 800 nm such that only DI of Au$^+$ can be observed. Based on the straightforward method for intensity estimation as discussed above, the intensity can be determined to be $\approx 4 \times 10^{14}$ W cm$^{-2}$. The momentum component parallel to the laser polarization direction, $p_\parallel$, is displayed in figures 5(a) and (b). For both channels, single and DI, a clear dependence of the momenta on the phase of the two-color field can be observed. The asymmetry map, $A(p_\parallel, \phi_r) = (Y_{\text{Up}} - Y_{\text{Down}})/(Y_{\text{Up}} + Y_{\text{Down}})$, calculated from the ion yields $Y$ detected in the lower or upper hemisphere in direction of the laser polarization, is displayed in (c) and (d) and shows that the degree of control is quite significant. Note, the momentum distribution of single ionization (SI) is partially overlaid by fragments from the dissociation of Au$^{2+}$ (see figure 1). It creates a background independent of the phase, since dissociation of Au$^{2+}$ occurs mainly from excited...
states without laser interaction. By comparison, the asymmetry is larger for DI, which can be explained by the fact that SI is strongly saturated and less sensitive on small variations of the field by the relative phase [31]. This can be seen in the phase-dependent yield displayed in figure 5(f), too. As expected, for SI and DI the yields and the shifts of the momenta induced by changing the relative phase follow a sinusoidal dependence (see figure 5(e)), whereby the modulations of the momenta feature a 2π-periodicity, while the yield has a π-periodicity.

In order to allow for a quantitative comparison of the results with theoretical predictions, we performed additional simulations using the semiclassical ionization model. In the simulation 100 000 electron trajectories per relative phase are computed based on an intensity distribution taking into account the focal volume effect and averaging over the carrier–envelope-phase of the laser pulse with frequency ω. Like for the analysis of the first measurement (see section 4), the model assumes that both ionization events in the SDI process are only linked by the ionization rates determined by the laser field.

The predicted relative-phase dependence for the ω−2ω-measurements of SI and DI of Au+−ions are displayed in figure 6. Good agreement between the measured and the simulated phase-dependent momentum distributions (see figure 5) is obtained for an intensity of 2.5 ·10¹⁴ W cm⁻², and an intensity ratio of 2.75% between 2ω and ω. The phase dependent shift of the measured momenta along polarization direction of the field is well reproduced (see figures 6(c) and (d)).

Comparing the width of the measured and simulated distributions (see (a) and (b) of figures 5 and 6) shows, that the simulation predicts again a significantly narrower distribution. However, a clear control of the momenta by the subcycle field is achieved and experimentally resolved. Further, for the measured phase-dependent mean momenta for SI and DI, good agreement with the simulation can be reported. In particular, the phase dependence for both ionization channels is well reproduces, which suggests that the observed ionization dynamics is governed by sequential ionization [40].

It should be noted that, in the simulation, the Coulomb interaction between electron and the ion after ionization is neglected as well as multi-electron effects such as nonsequential DI. In fact, upon closer comparison of figures 5(b) and 6(b) one notices that in the experimental data the phases at which the yield peaks (red colors) are not symmetric to the phase where $p_\parallel$ is extremal—in contrast to the computed data.

5. Conclusion

We have introduced a LMIS into strong-field laser physics. The new ion source will considerably expand the range of available atomic and molecular species for experiments. In the present work, we used field evaporation of an alloy of gold and silicon and studied strong-field ionization of Au⁺ and Si²⁺ ion beam targets by intense femtosecond laser pulses. With laser intensities of up to 4 ·10¹⁶ W cm⁻², ten-fold ionization of Au⁺ and DI of Si²⁺−ions were observed. The observed highly nonlinear multiple ionization dynamics are analyzed and compared to theoretical predictions based on quasistatic tunnel ionization rates [36] under the assumption of a sequence of independent ionization events. Further, we investigated the shift of the ion momentum after electron removal in a sculpted femtosecond laser field. Using an efficient and reliable method to control the momenta by a two-color-laser field, we demonstrate that the Au⁺−beam allows for recoil ion momentum detection.

Good agreement between measurement and simulation for both measurements shows that a semiclassical model of sequential strong-field ionization provides insights in the strong field interaction of gold ions, which are distinguished from more conventional targets by numerous electrons in the valence shell and many closely lying bound states. The results highlight the possibility of measuring and controlling multi-electron dynamics in complex systems on the attosecond time scale by fine tuning the field evolution of intense laser pulses. For an exact description of these systems, there is a need for much more precise theoretical calculations and more sophisticated theory [13].

Furthermore, our result represents an important step in the extension of strong-field phenomena to unconventional targets as metal and metalloid ions are for example important for understanding the behavior of transition metal dimers and clusters in heterogeneous catalytic processes [41]. In general, we expect this ion source type to provide many new opportunities to explore light–matter-interactions in almost the entire and hitherto largely unexplored part of the periodic table of elements [28].

Acknowledgments

The authors acknowledge funding by the Deutsche Forschungsgemeinschaft (DFG) in the frame of the Schwerpunktprogramm (SPP) 1840, Quantum Dynamics in Tailored Intense Fields. We thank Dr L Bischoff, Dr N Klinger and W Pilz from the Ion Beam Center at the Helmholtz-Zentrum Dresden-Rossendorf e.V., a member of the Helmholtz Association for help with the preparation of the emitter of the LMIS. We thank T Weber and F Ronneberger for technical assistance and S L Döpfner for assistance in the characterization of the source.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Bo Ying @ https://orcid.org/0000-0002-9573-5354
Frank Machalett @ https://orcid.org/0000-0003-2799-8889
Vanessa Huth @ https://orcid.org/0000-0002-8125-666X
Matthias Kübel @ https://orcid.org/0000-0001-6065-6122
Thomas Stöhlker @ https://orcid.org/0000-0003-0461-3560
Gerhard G Paulus @ https://orcid.org/0000-0002-8343-8811
Philipp Wustelt @ https://orcid.org/0000-0002-8674-8444
References

[1] Brabec T and Krausz F 2000 Rev. Mod. Phys. 72 545
[2] Krausz F and Ivanov M 2009 Rev. Mod. Phys. 81 163
[3] Becker W, Liu X, Ho P J and Eberly J H 2012 Rev. Mod. Phys. 84 1011
[4] L'Huillier A, Lompre L A, Mainfray G and Manus C 1983 Phys. Rev. A 27 2503
[5] Walker B, Sheehy B, DiMauro L F, Agostini P, Schafer K J and Kulander K C 2005 Phys. Rev. Lett. 94 053602
[6] Augst S, Meyerhofer D D, Strickland D and Chin S L 1989 Phys. Rev. Lett. 63 664

[7] Lan P, Zhou Y, Pfeiffer A N, Zhang Q, Lu P and Midorikawa K 2014 Phys. Rev. A 89 033424
[8] Emmanouilidou A, Chen A, Hofmann C, Keller U and Landsman A S 2015 J. Phys. B: At. Mol. Opt. Phys. 48 245602
[9] Uiberacker M et al 2007 Nature 446 627
[10] Moshammer R et al 2000 Phys. Rev. Lett. 84 447
[11] Wustelt P, Möller M, Rathje T, Sayler A M, Stöhlker T and Paulus G G 2015 Phys. Rev. A 91 031401
[12] Machelett F 1992 Untersuchung zum Einsatz binärer und ternärer eutektischer Systeme in Flüssigmetall-Ionenquellen PhD Thesis Friedrich Schiller University Jena
[13] Yudin G and Ivanov M 2001 Phys. Rev. A 64 031409
[14] Schultz M, Bergues B, Schröder H, Krausz F and Kompa K L 2011 New J. Phys. 13 033001
[15] Sayler A M, Wang P Q, Carnes K D and Ben-Itzhak I 2007 J. Phys. B: At. Mol. Opt. Phys. 40 4367
[16] Wang P, Sayler A M, Carnes K D, Esry B D and Ben-Itzhak I 2005 Opt. Lett. 30 664
[17] Ammosov M V, Alnaser A S, Tong X M, Ulrich B, Ranitovic P, Ghimire S, Chang Z, Litvinyuk I V and Cocke C L 2005 Phys. Rev. A 72 041403
[18] Weber T et al 2000 Nature 405 658
[19] Pfeiffer A N, Cirelli C, Smolarski M, Wang X, Eberly J H, Dörner R and Keller U 2011 New J. Phys. 13 093008
[20] Pfeiffer A N, Cirelli C, Smolarski M, Dörner R and Keller U 2011 Nat. Phys. 7 428
[21] Pfeiffer A, Sayres S G and Leone S R 2013 Mol. Phys. 111 2283–91
[22] Ludwig A, Maurer J, Meyer B W, Phillips C R, Gallmann L and Keller U 2014 Phys. Rev. Lett. 113 243001
[23] Yudin G and Ivanov M 2001 Phys. Rev. A 64 031409
[24] Schulz M, Bergues B, Schröder H, Krausz F and Kompa K L 2011 New J. Phys. 13 033001
[25] Sayler A M, Wang P Q, Carnes K D and Ben-Itzhak I 2007 J. Phys. B: At. Mol. Opt. Phys. 40 4367
[26] Wang P, Sayler A M, Carnes K D, Esry B D and Ben-Itzhak I 2005 Opt. Lett. 30 664
[27] Ammosov M V, Delone N B and Krainov V P 1986 Sov. Phys. JETP 64 1191–6
[28] Chen C, Yin Y-Y and Elliott D S 1990 Phys. Rev. Lett. 64 507
[29] Xie X et al 2013 New J. Phys. 15 043050
[30] Würzler D, Skruszewicz S, Sayler A M, Zille D, Möller M, Wustelt P, Zhang Y, Tiggiesbäumker J and Paulus G G 2020 Phys. Rev. A 101 033416
[31] Machelett F 1992 Untersuchung zum Einsatz binärer und ternärer eutektischer Systeme in Flüssigmetall-Ionenquellen PhD Thesis Friedrich Schiller University Jena
[32] Augst S, Strickland D, Meyerhofer D D, Chin S L and Eberly J H 1989 Phys. Rev. Lett. 63 2212
[33] Wustelt P, Max M, Sch M S, Xie X, Hansu V, Sayler A M, Baltuska A, Paulus G G and Kitzler M 2017 Phys. Rev. A 95 023411
[34] Schultze M, Bergues B, Schröder H, Krausz F and Kompa K L 2011 New J. Phys. 13 033001
[35] Sayler A M, Wang P Q, Carnes K D and Ben-Itzhak I 2007 J. Phys. B: At. Mol. Opt. Phys. 40 4367
[36] Wang P, Sayler A M, Carnes K D, Esry B D and Ben-Itzhak I 2005 Opt. Lett. 30 664
[37] Ammosov M V, Delone N B and Krainov V P 1986 Sov. Phys. JETP 64 1191–6
[38] Chen C, Yin Y-Y and Elliott D S 1990 Phys. Rev. Lett. 64 507
[39] Xie X et al 2013 New J. Phys. 15 043050
[40] Würzler D, Skruszewicz S, Sayler A M, Zille D, Möller M, Wustelt P, Zhang Y, Tiggiesbäumker J and Paulus G G 2020 Phys. Rev. A 101 033416
[41] Herrera R P and Gimeno M C 2021 Chem. Rev. 121 8311