Attosecond spatial control of electron wave packet emission dynamics

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Abstract: Using orthogonally polarized two-color laser fields on neon and coincidence momentum imaging we gain access to the Coulomb influence in single ionization on sub-cycle times, and demonstrate a strong electron-electron anti-correlation in double ionization.

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Angström and attosecond control of free electron wave packets is one of the pinnacles of attosecond science. Orthogonally polarized two-color (OTC) laser fields allow to control the motion of field-ionizing electronic wave packets both in time and space [1]. In OTC pulses time and space are connected and thus an attosecond time scale is established in the polarization plane for both the emitted and the re-colliding wave packets [2].

Here, we report on experiments that use OTC pulses for studying single and double ionization of neon using the COLTRIMS technique. By exploiting the time-to-angle mapping inherent to OTC pulses [2] we gain access to the sub-cycle timing of the wave packet release from the momentum vector of emitted electrons. This allows us to study the influence of the parent ion's field on the trajectories of tunneling electrons during single ionization. In double ionization we demonstrate control over the correlated emission of two electrons in the intensity regime of nonsequential double ionization. We observe a strong electron-electron anti-correlation.

In the experiments the OTC pulses (one cycle of the field is shown in Fig. 1(a)) were produced by combining an 800 nm laser pulse, frequency ω, and its second harmonic pulse, frequency 2ω, in a collinear geometry at a rate of 5 kHz. The light intensity in either color was $I_{800\mathrm{nm}} = I_{400\mathrm{nm}} = (1 \pm 0.1) \times 10^{14}$ W/cm^2. Figs. 1(b)-(f) show measured momentum distributions of electrons correlated with Ne^+ in the polarization plane of the OTC field. The spectra show that the electron emission direction is highly sensitive to the shape of the OTC field, featuring asymmetric emission patterns that vary with $\Delta\varphi$. The x-shaped central structure of the measured photo-electron spectra can be related to the 2D-evolution of the vector potential. However, this correspondence fails for certain $\Delta\varphi$. By exploiting the time to

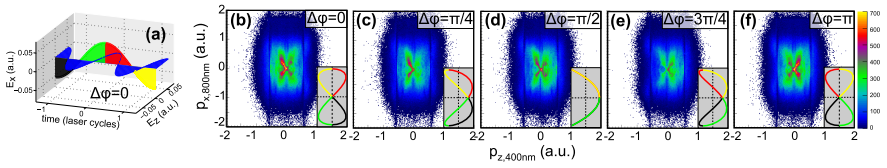

Fig. 1. **(a)** Separate electric fields of the 400 nm (blue) and 800 nm pulses. The colors encode quarter cycles of the 800 nm field. **(b)-(f)** Measured electron momentum distributions correlated to Ne^+ in the polarization plane of the OTC field (xz) with $|p_y| < 0.1$ a.u. for selected $\Delta\varphi$ from 0 to π. The insets illustrate the classical prediction $\vec{p} = -\vec{A}(t_0)$ of the electron momentum. The color code is illustrated in (a).

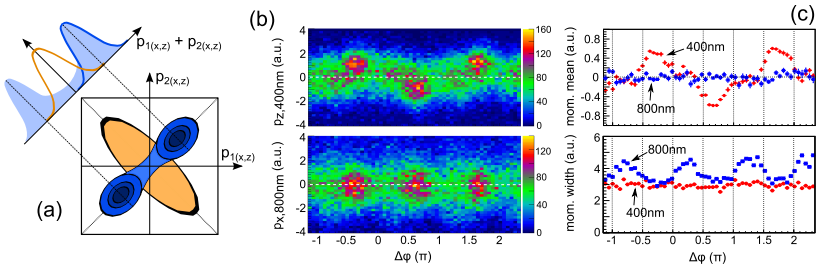

Fig. 2. **(a)** Signatures of correlated (blue) and anti-correlated (orange) two-electron emission dynamics in two-electron (lower right) and ion (upper left) momentum spectra. **(b)** Ne^{2+} p_z momentum (other directions integrated over) as a function of relative phase $\Delta\varphi$ (upper panel). Ne^{2+} p_x momentum (lower panel). **(c)** $\Delta\varphi$-dependent mean value of p_z (red dots) and p_x (blue squares). lower panel: width of p_z (red dots) and p_x (blue squares).

momentum space mapping provided by OTC fields in combination with the intricate insight into the electron wave packet dynamics in the OTC field obtained from simulations based on a semi-classical trajectory model with and without the ionic Coulomb potential included [3], and by numerically solving the time-dependent Schrödinger equation in three spatial dimensions (TDSE), we succeeded in gaining access to the dynamics of emitted and recolliding electron wave packets on laser-sub-cycle times. In particular we investigated the influence of the ionic Coulomb field on the wave packets and found evidence for a strong Coulomb focusing of recollision trajectories, as we will show in detail during our conference presentation.

We now turn to nonsequential double ionization (NSDI) with OTC pulses. For these experiments the intensity has been increased to $I_{800\text{nm}} = I_{400\text{nm}} = (2 \pm 0.2) \times 10^{14}$ W/cm^2. Analysis of the spectra of the electron sum momentum vector in terms of its mean values and widths along p_x and p_z allows obtaining detailed insight into the correlated electron emission dynamics [Fig. 2(a)]. Correlated two electron-emission (indicated in blue) results either in a large width and zero mean value, if it takes place symmetrically into both hemispheres (blue area), or in a narrow width and large mean value if it happens dominantly into one hemisphere (blue thick line). Anti-correlated two electron-emission (indicated in orange) manifests itself as a narrow ion momentum spectrum with zero mean value (orange line). Fig. 2(b) plots the momentum spectra of Ne^{2+} along the p_z and p_x momentum components as a function of $\Delta\varphi$, and Fig. 2(c) their widths and mean values. One scenario that can explain the small momentum width measured when the total double ionization probability maximizes, is that the two electrons are emitted into opposite $p_{x,800\text{nm}}$-hemispheres in a strongly anti-correlated emission scenario [see Fig. 2(a)]. For those phases where the spectral width is large, the emission happens in a correlated manner with emissions alternately into both hemispheres, which leads to spectra as sketched by the blue areas in Fig. 2(a). Thus, our measurements demonstrate that by using OTC laser fields it is possible to control the electron-electron (anti-)correlation during NSDI by using $\Delta\varphi$ as the control parameter.

In conclusion, we used the COLTRIMS technique to investigate for the first time atomic single and double ionization by OTC laser fields. By exploiting the time to momentum space mapping provided by OTC fields we succeeded in gaining experimental access to the dynamics of emitted and recolliding electron wave packets on laser-sub-cycle times. We furthermore showed that by tuning the shape of the electric field of the OTC pulses on the sub-cycle scale it is possible to control the two electron-emission dynamics in nonsequential double ionization, and to dictate whether the two electrons are predominantly emitted in a correlated or anti-correlated manner.

References

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