Electron Matter-Wave Vortices in Double Photoionization of Helium by Attosecond Pulses

J.M. Ngoko Djiokap*[1], A.V. Meremianin†, N.L. Manakov†, S.X. Hu‡, L.B. Madsen§, and Anthony F. Starace*[2]

* Department of Physics and Astronomy, University of Nebraska, Lincoln, Nebraska 68588-0299, USA
† Department of Physics, Voronezh State University, Voronezh 394006, Russia
‡ Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623-1299, USA
§ Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark

Double photoionization of helium by a pair of time-delayed, elliptically-polarized attosecond pulses is shown to produce two-electron momentum distributions that exibit *two*-start spiral vortex structures. These structures originate from Ramsey interference of the created pair of two-electron wavepackets, each carrying a total angular momentum of unity. The predicted vortex-shaped patterns occur for any energy partitioning between electrons, and are exquisitely sensitive to the time delay between the two pulses, their relative phase, their ellipticity and handedness. Moreover, these kinds of vortices occur for both in-plane (cf. Figs. 1, 2) and out-of-plane detection geometries; however, they only occur for fixed angular separation $\hat{\mathbf{p}}_1 \cdot \hat{\mathbf{p}}_2$ between the electron momenta.

We solve *ab initio* the seven-dimensional two-electron, time-dependent Schrödinger equation and analyze the results using perturbation theory. Such vortices are general phenomena, as similar patterns have been predicted for both atomic [1] and molecular [2] single-electron ionization processes. Recently, similar Fermat spiral vortices were observed in an experiment [3] involving femtosecond multiphoton ionization of potassium. Those results are consistent with our theoretical predictions for both photoionization [1] and multiphoton ionization [4] of helium.

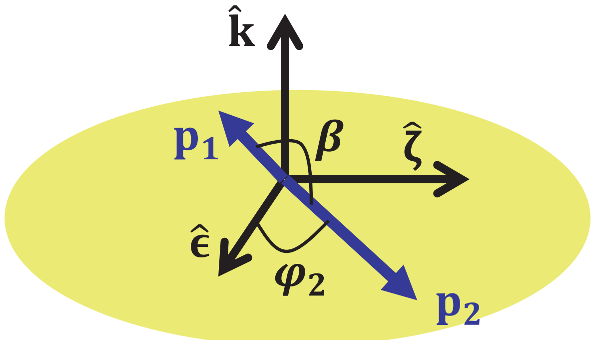

Figure 1. In-plane detection geometry in which $\mathbf{p}_1, \mathbf{p}_2$ are ejected back-to-back (BTB) with unequal energy sharing (UES). This plane is defined by the major ($\hat{\epsilon}$) and minor ($\hat{\zeta}$) axes of the polarization ellipse; it is orthogonal to the laser propagation direction, $\hat{\mathbf{k}}$.

[1] E-mail: marcelngoko@unl.edu
[2] E-mail: astarace1@unl.edu

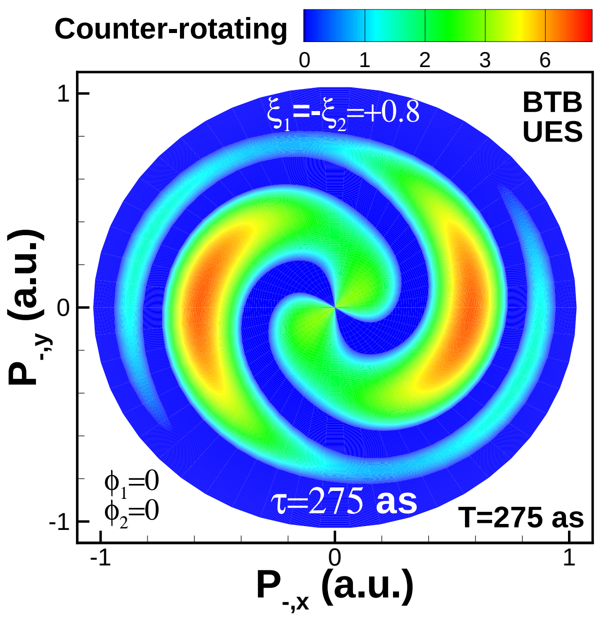

Figure 2. Fermat spiral vortex pattern in double ionization of He by a pair of oppositely elliptically polarized attosecond pulses (with degrees of circular polarization $\xi_1 = -\xi_2 = +0.8$) for the detection geometry in Fig. 1. The vortex pattern is exhibited by the $\mathbf{P}_-$ distribution in the polarization plane, where $\mathbf{P}_- = (\mathbf{p}_1 - \mathbf{p}_2)/2$ defines the relative momentum of the ionized pair of electrons. The two pulses have the same carrier frequency of 90 eV; intensity of 50 TW/cm^2; carrier-envelope phase $\phi_1 = \phi_2 = 0$; and are delayed in time by $\tau = T$, where $T = 275$ as is the total duration of the six-cycle pulses.

Research supported in part by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, Grant No. DE-FG02-96ER14646.

References

[1] J.M. Ngoko Djiokap *et al.* 2015 *Phys. Rev. Lett.* **115** 113004

[2] K.-J. Yuan *et al.* 2016 *Phys. Rev. A* **93** 053425

[3] D. Pengel *et al.* 2017 *Phys. Rev. Lett.* **118** 053003

[4] J.M. Ngoko Djiokap *et al.* 2016 *Phys. Rev. A* **94** 013408