Interference of electrons resulting from the photoionization of an atom in an electric field

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During photoionization in a uniform electric field, the trajectories of electrons emitted from an atom in different directions may intersect again at a large distance from the atom, creating an interference pattern. Under favorable conditions this pattern could be observed in a direct experiment.

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Let us consider a coherent, monoenergetic source of electrons of energy E (for example, an atom or molecule undergoing photoionization) in a uniform electric field of intensity $\mathscr{E}$. This field leads to the formation of an interference pattern on a screen placed at a certain distance z_0 from the atom and oriented perpendicular to the field. The interference corresponds to the existence of two (or more, if there is a Coulomb interaction of the electrons with the source) classical electron trajectories which run from the source to the same point on the screen. Evidence of this interference can be seen in the oscillation of the total effective photoionization cross section discussed in Refs. 1–3. In this letter we wish to point out that under favorable conditions the interference pattern could reach macroscopic dimensions and could be observed in a direct experiment.

In the absence of a final-state Coulomb interaction (the photodetachment of an electron from a negative ion) the pattern can be described in the semiclassical approximation used in Ref. 3. The dimensions of the pattern are determined by the parameters $l = k^2/\mathscr{E}$ and $l = k^3/\mathscr{E}$, where $k = (2E)^{1/2}$ (atomic units are being used here except where otherwise stipulated). According to Ref. 3, at $z_0 \gg l$, for an isotropic source, the z component of the photoelectron current density crossing the plane of the screen, $z = -z_0$ (the z axis passes through the atom in the direction parallel to the field, and ρ is the distance from this axis), may be written as follows:

$$j_z \approx \frac{I[1+\cos(\Delta S)]}{2\pi\rho_{max}^2(1-\rho^2/\rho_{max}^2)^{1/2}} \qquad (\rho \lesssim \rho_{max}) \quad , \tag{1}$$

where I is the intensity of the source, $\rho_{\max} = (2lz_0 + l^2)^{1/2} \approx (2lz_0)^{1/2}$ is the radius of the interference pattern, and $\Delta S \approx 2/3\nu(1-\rho^2/\rho_{\max}^2)^{3/2}$ is the difference between the values of the approximate action for motion along the two trajectories leading to the given point on the screen. At $\rho = \rho_{\max}$, the ρ dependence of j_z is determined by the square of an Airy function (Fig. 1).

For a fixed number of rings, i.e., for a fixed value of ν (which specifies the relationship between the energy E and the field intensity), we have $\rho_{\max} \sim E^{-1/4}$. A

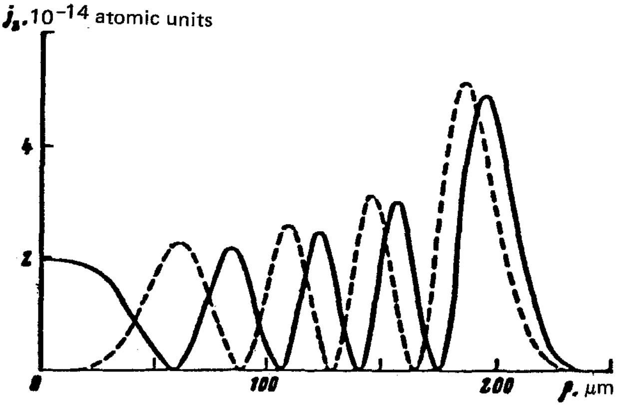

FIG. 1. Interference pattern produced by an isotropic electron source of unit intensity in the absence of a final-state Coulomb interaction. Solid curve–$E = 10\ \text{cm}^{-1}$, $\mathscr{E} = 112$ V/cm (corresponding to a maximum in the total cross section); dashed curve $E = 9.3\ \text{cm}^{-1}$, $\mathscr{E} = 112$ V/cm (corresponding to a minimum in the total cross section).

lower limit is set on the possible energy range by the energy spread of the electron source, which may be caused by the nonzero temperature (T) of the gas whose atoms are being ionized and also by the nonzero spectral width δE_L of the ionizing light: $E \gg 4(m/M\, k_B T + \delta E_L)$, where m and M are the masses of the electron and the atom, respectively, and k_B is the Boltzmann constant. For the experimental apparatus currently in use, the spread δE_L ranges from 0.5 (Ref. 1) to $2 \times 10^{-3}\ \text{cm}^{-1}$ (Ref. 4). The latter value is of the order of the thermal energy spread of electrons at $T = 500$ K.

At an energy $E = 10\ \text{cm}^{-1}$ and a field intensity $\mathscr{E} = 112$ V/cm the interference pattern consists of five rings and has a radius of 210 μm at a distance $z_0 = 10$ cm from the atom. Such a pattern could be observed experimentally, since the position of the atoms could be fixed within a few microns–much less than the distance between the rings–by using two-photon or many-photon ionization at a laser focus. The pattern could be magnified further by ordinary electron-optics methods. The restriction on the dimension of the source along the z axis, δz, is even less stringent: $\delta z \ll 2z_0$.

The Coulomb interaction of the photoelectron with the atomic core increases the transverse momentum component of the photoelectron and hence the radius of the interference pattern. Furthermore, with a Coulomb interaction the interference pattern also arises at energies $E < 0$; the corresponding photon energies lie below the ionization potential of the atom.

At a resonance in a quasibound state in superimposed Coulomb and uniform fields it is a simple matter to calculate the current density in the parabolic coordinates $\xi = r + z$, $\eta = r - z$. The current-density component directed perpendicular to the surface $\eta = \text{const} \gg l$ can be expressed in terms of the solution $\chi_1(\xi)$ of the equation in the parabolic coordinate ξ (Refs. 2 and 5):

$$i_\eta \sim \chi_1^2(\xi)/\xi\ . \tag{2}$$

At resonance, the interference pattern is thus described within a factor ξ^{-1} by the square of the wave function for the finite motion along the coordinate ξ. The radius of the pattern is determined by the dimension of the classically allowed region along the coordinate ξ:

$$\rho_{max}^{c} = [l + (l^2 + 4z_1/\mathscr{E})^{1/2}]^{1/2} z_0^{1/2} > \rho_{max} \tag{3}$$

The radii of the nodes are $\rho_n = (2\xi_n z_0)^{1/2}$, where ξ_n is the nth zero of $\chi_1(\xi)$. The outer rings are the widest. At $E > 0$, their dimensions are approximately the same as those of rings produced without a Coulomb interaction (the existence of quasibound states at $E > 0$ is indicated by the experimental data of Ref. 1 and by the shape of the classical photoelectron trajectories studied in Ref. 2).

In addition to furnishing information on the electron-density distribution at the resonance in the quasibound state [expression (2)], the interference pattern can be used to measure the ionization potentials of atoms and the electron affinities; these measurements would be more accurate than the existing methods based on the threshold features of the photoionization and photodetachment cross sections or other atomic excitation methods (see Ref. 6 and the literature cited there). The radius of the pattern depends on the energy E, which is equal to the difference between the photon energy and the ionization potential of the atom (or the electron affinity), and this radius changes sharply, according to (3), upon a slight change in E in weak fields $\mathscr{E} \ll 1$. It may prove sufficient to measure the radius of the pattern at a single value of the energy, in contrast with the methods currently being used,[6] which require analysis of spectral regions. There is also the possibility of selectively detecting atoms or molecules of a particular species in a gas or adsorbed on a solid surface. An apparatus designed for observing and measuring the photoionization interference of electrons could thus be labeled a "photoionization microscope."

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