Tomography of Rydberg states via electric-field induced tunneling

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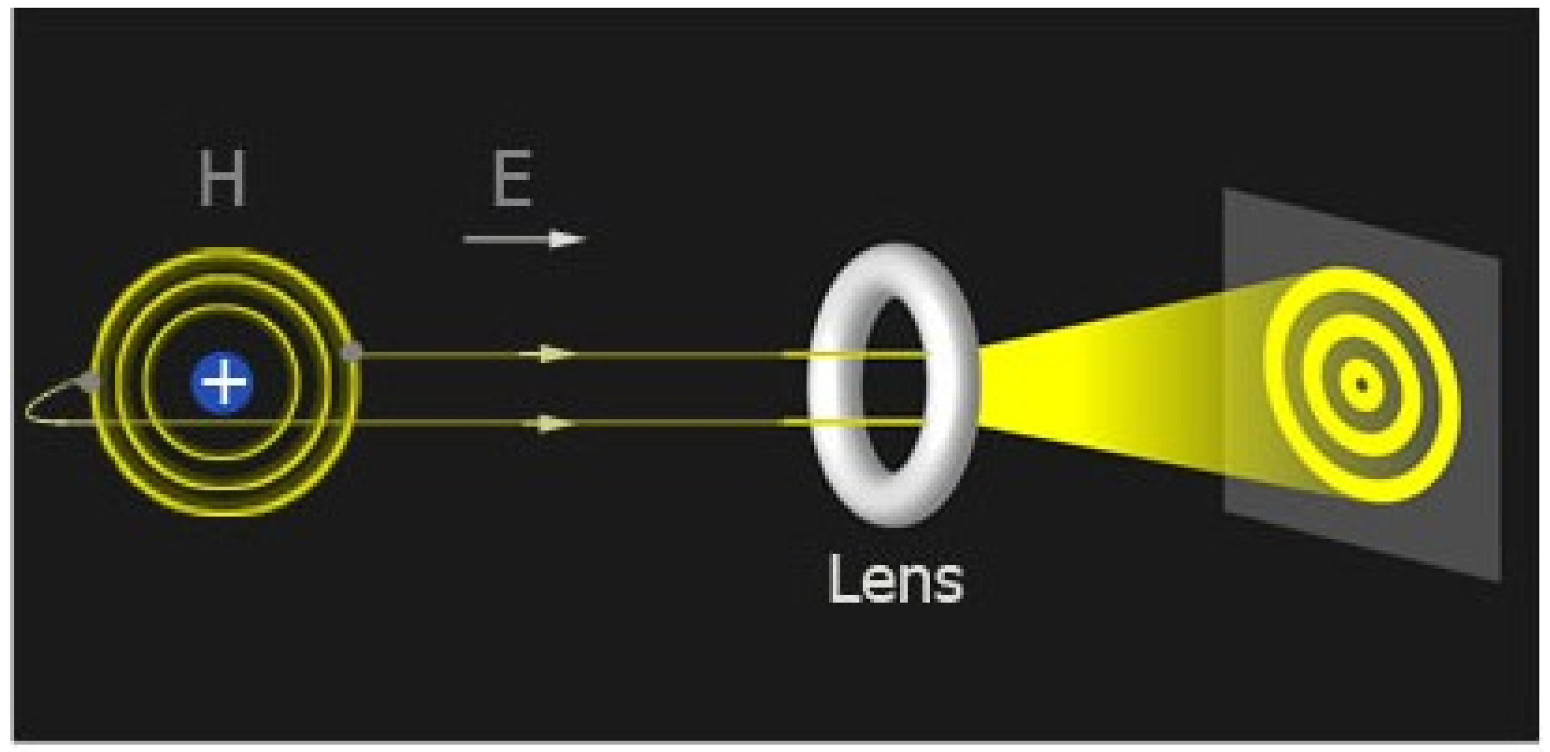
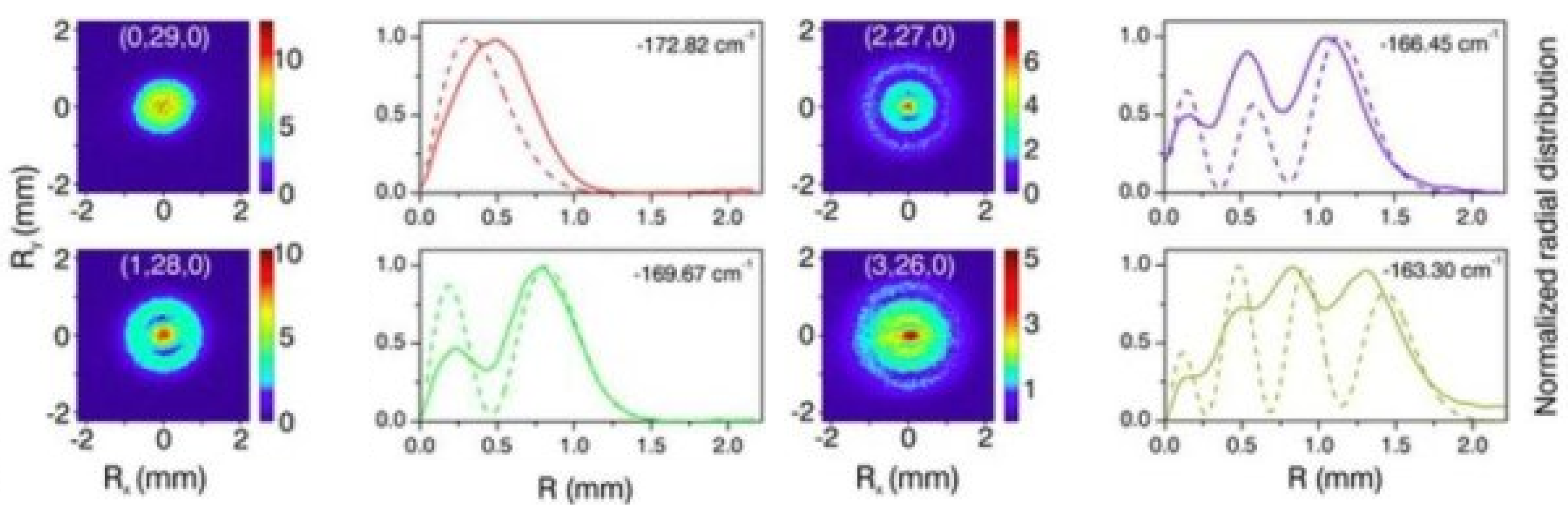
Introduction

The wave-function microscopy is expected nowadays to be a powerful tool in quantum states tomography. This method was realized in the experiments with hydrogen [3], xenon [5] and lithium [6] atoms. The main idea is to explore the transverse nodal structure of the photoelectron state by the interference pattern formed by its different paths to the screen (along and against the external electric field).



In the recent experiment by Stodolna et al. [3] a hydrogen atom prepared in the mixture of 2s and 2p states and placed in a constant uniform electric field is ionized by a laser pulse that is polarized along the field. The Stark states of the electrons considered in the parabolic coordinates are determined by the parabolic quantum numbers n_1 and n_2 that are related to the principal quantum number as follows: $n = n_1 + n_2 + |m| + 1$.The photoelectron is accelerated in the external electric field, passes through a lens and finally gets to the screen. The role of the screen plays a two-dimensional photodetector that records the photoelectrons. For a beam of hydrogen atoms one observes the interference pattern on the screen.



The interference patterns obtained for the states $(n_1, n_2, m) = (0, 29, 0), (1, 28, 0), (2, 27, 0), (3, 26, 0)$[3].

Feedback

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The method

The aim of this work is perform a theoretical description of the photoionization tomography experiments and to find the relation between the spatial distribution of the photoelectron current and the state of the electron in the hydrogen atom. We use the following model. The system is considered as a Rydberg atom placed in a weak constant uniform electric field. The electron is in a bound state with a negative energy. One can demonstrate that for these highly excited states we can cut the tails of the Coulomb potential. After the underbarrier tunneling induced by an electric field the ionized electron gets to the screen. We consider a reverse tomographic problem supposing that we prepare the highly excited electron in a definite state $\psi(x, y, z, t_0)$. Than we consider the evolution of this state in terms of the Green function and obtain the probability density of the electron state on the plane of the screen.

References

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Acknowledgments

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Conclusion

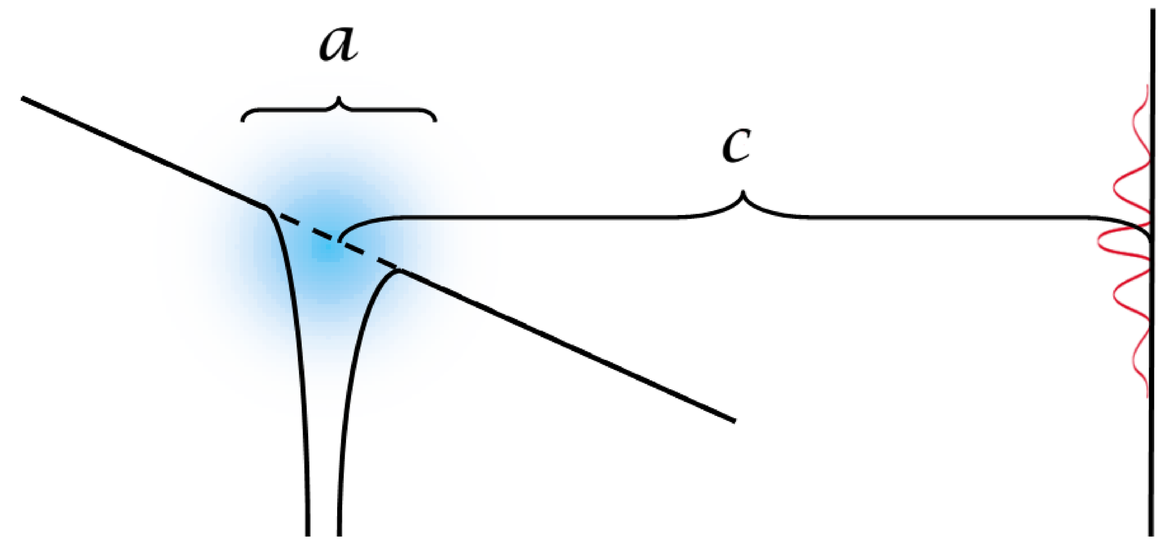
The presented theoretical description can be used for restoring some parameters of an outer electron state. It is also possible to generalize the photoionization tomography method. For instance one can consider the case, when the atom is placed in a magnetic field or in a non-homogeneous electric field. It might help to reconstruct a phase of an initial state of the electron.

Description excluding atomic potential

Excluding the potential of the atom, the evolution of the wave function is described by the expression

$$\psi(T, \boldsymbol{x}) = \frac{1}{Z}\int \exp\left\{ i\left[\frac{(\boldsymbol{x}-\boldsymbol{y})^2}{2T} + \frac{1}{2}\boldsymbol{E}(\boldsymbol{x}+\boldsymbol{y})T\right]\right\}\psi(y)d^3y, \qquad (1)$$

where Z is a normalizing factor.



Since the atom is far away from the screen $c \gg a$, $|\boldsymbol{E}|T^2 \gg a$ and $\frac{|\boldsymbol{E}|T^2}{2} \approx c$, where $\frac{|\boldsymbol{E}|T^2}{2}$ is the distance from the atom to the electron at the time T. (We assume that $t_0 = 0$). Using these relations we obtain for the Green function:

$$G(\boldsymbol{x}, \boldsymbol{y}, T) = exp\left\{ i\left[\frac{(\boldsymbol{x}-\boldsymbol{y})^2}{2T} + \frac{1}{2}\boldsymbol{E}(\boldsymbol{x}+\boldsymbol{y})T\right]\right\} \approx$$
$$\approx \exp\left\{ i\left[\frac{(\boldsymbol{x}^2 - 2\boldsymbol{x}\boldsymbol{y})}{2T} + \frac{1}{2}\boldsymbol{E}(\boldsymbol{x}+\boldsymbol{y})T\right]\right\} =$$
$$\exp\left\{ i\left[\frac{\boldsymbol{x}^2 + T^2\boldsymbol{E}\boldsymbol{x} - (2\boldsymbol{x} - T^2\boldsymbol{E})\boldsymbol{y}}{2T}\right]\right\}. \qquad (2)$$

$$\psi(T, \boldsymbol{x}) = \frac{\sqrt{2\pi}}{Z}\exp\left\{ i\left[\frac{\boldsymbol{x}^2 + T^2\boldsymbol{E}\boldsymbol{x}}{2T}\right]\right\}\widetilde{\psi}\left(\frac{2\boldsymbol{x} - T^2\boldsymbol{E}}{2T}\right). \qquad (3)$$

Here $\widetilde{\psi}(y)$ is a Fourier transform of the initial wave function.

$$|\psi(\boldsymbol{x}, T)|^2 = \frac{2\pi}{Z^2}\left|\widetilde{\psi}\left(\frac{\boldsymbol{x} - \frac{T^2\boldsymbol{E}}{2}}{T}\right)\right|^2. \qquad (4)$$

The typical width of the wave function after time T is $x_0 \approx \frac{T}{a}$. Using $\frac{|\boldsymbol{E}|T^2}{2} \approx c$ we get $x_0 = \sqrt{\frac{2c}{a^2|\boldsymbol{E}|}}$. We consider the electric field, for which $c \gg x_0$. The equation (4) performs the relation between the probability density of the electron in the Rydberg atom and the spatial distribution of the probability current on the screen. This result can be used to get the information about the phase of the initial state via the maximum-likelihood reconstruction method.