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Dependence of Rydberg Yield on Ellipticity in Strong Field Ionization

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Abstract. We obtain a probability distribution of Rydberg yield that shows close agreement with recent experimental results. Contrary to general expectations, we find that rescattering is not a significant mechanism in the creation of excited neutrals.

1 Introduction

Rydberg states can be created when the tunneled electron does not gain sufficient energy from the laser pulse and is subsequently captured by the Coulomb field, creating an excited neutral atom. While some progress has been made in analyzing the generation of Rydberg states in linearly polarized light [1,2], the role of polarization, and in particular the dramatic decline of Rydberg states with increasing ellipticity of light remains to be explained. Here, we clarify this dependence of Rydberg state generation on ellipticity, deriving a probability distribution which shows excellent agreement with experimental [3] and numerical data, and which furthermore quantifies the dependence of Rydberg states on laser field intensity. Our results, which show rescattering is not important to the creation of Rydberg states, contradict the proposed mechanism in [3] that interprets the same experimental data as providing "strong experimental support" for a rescattering process.

We also present experimental results that provide indirect information on Rydberg state generation by measuring the yield of $E \approx 0$ states at the detector as a function of ϵ. $E \approx 0$ states can be considered as a cut-off for Rydberg states since the condition defining the Rydberg state (with the corresponding quantum number, n) is given by: $E = -1/2n^2 < 0$. Our experiment is consistent with the findings in [3] in that it also shows the cut-off in Rydberg state generation close to $\epsilon \approx 0.3$.

2 Electron dynamics after ionization

2.1 Analytical results

The electric field of a laser propagating in the z-direction is given by:

$$\mathbf{F}(t) = \frac{-F_0 f(t)}{\sqrt{\epsilon^2+1}}[\cos(\omega t)\,\hat{x} + \epsilon sin(\omega t)\,\hat{y}] \tag{1}$$

where ω is the frequency of the laser, ϵ is the ellipticity (the major axis of polarization is along $\hat{x}$), and $f(t)$ is the slowly-varying pulse envelope: $f_{max} = f(0) = 1$. In our analysis, we neglect the Coulomb field after ionization, approximating electron trajectories as being determined by the laser field only, given by Eqn. (1).

The overall structure of the derivation of Rydberg yield is (see [4] for more detail): We show that the electrons end up far from the exit point, x_e, after the laser pulse has passed. This imposes a zero

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final momentum condition. While the momentum along x is close to zero due to ionization at the peak, the final transverse momentum at the exit point needs to cancel out the drift velocity created by the laser field. Therefore, the probability of a Rydberg state can be obtained from the probability that the transverse velocity at the exit point (which is itself given by the ADK probability distribution) is such that it approximately cancels the deterministic drift velocity.

The derived probability distribution for Rydberg yield is then given by [5],

$$P_0 = exp\left(-2(2I_p)^{3/2}\sqrt{1+\epsilon^2}/3F_0\right) \tag{2}$$

where I_p is the ionization potential. The exponent of P_0 can be further Taylor expanded to obtain,

$$P_R(\epsilon) \approx e^{\frac{-2(2I_p)^{3/2}}{3F_0}} e^{-\epsilon^2/2\sigma_\epsilon^2} \tag{3}$$

where σ_ϵ is the standard deviation of the Gaussian probability distribution for Rydberg state yield as a function of ellipticity of light:

$$\sigma_\epsilon = \sqrt{\frac{3}{3+\gamma^2}} \frac{\omega}{\sqrt{2F_0}\left(2I_p\right)^{1/4}} \tag{4}$$

In deriving Eqn. (3) a Taylor expansion was used, retaining only terms up to the order of ϵ^2, since $\epsilon^2 \ll 1$ (the Rydberg state generation is only found at small values of ϵ). In the tunneling regime where $\gamma \ll 1$, Eqn. (4) can be approximated as: $\sigma_\epsilon = \omega/\sqrt{2F_0}(2I_p)^{1/4}$.

2.2 Comparison to experiment

A comparison between the experimental data (taken from [3]), simulations and analytically obtained curve given by Eqn. (3) is shown in Fig. 1. The intensity and laser frequency used in the figure were chosen for the purposes of comparison with the experiment in [3]. While the total ion yield varies slowly with increasing ellipticity, the yield of Rydberg states drastically decreases to essentially zero for $\epsilon > 0.3$. This holds true over a wide span of intensities ($0.35-3PW/cm^2$), where analysis (see Eqn. (3)) and numerics show the disappearance of Rydberg states in the $0.2 < \epsilon < 0.3$ range, depending on field strength. This dramatic decrease with ellipticity is also typical of a rescattering process as measured for HHG and Non-Sequential Multiple Ionization (NSMI) [3,6] .

The experimental setup was as follows: a laser pulse of duration $\tau_p = 33fs$, central wavelength $\lambda_0 = 788nm$, and peak intensity of $0.8PW/cm^2$ (CEO phase [7] was not stabilized) was produced by a Ti:Sapphire laser system focused onto helium atoms in a cold gas jet, with the gas jet density adjusted such that on average much less then one ionization occurs per laser shot. A COLTRIMS setup [8] measures the ion momentum, which is the negative of the electron momentum due to momentum conservation. The momentum resolution is 0.1 a.u. in time-of-flight direction and 0.9 a.u. in gas jet direction, mainly determined by thermal spread. A broadband quarter-wave plate is used to alter the ellipticity of the laser pulses. In the final analysis, the ellipticity and the angular orientation of the polarization ellipse are calculated from the angle of the quarter-wave plate, respecting its wavelength dependence [9]. The knowledge of the ellipticity and the angle of the polarization ellipse for each detected ion allow generating ellipticity-resolved spectra with a high resolution.

The experimental results are presented in Fig. 2. Figure 2 (a) shows that $E \approx 0$ states decline dramatically and virtually disappear for $\epsilon > 0.3$, in agreement with theory and numerics, shown in Fig. 1, which also predict the disappearance of Rydberg states (defined as $E \leq 0$) close to $\epsilon \approx 0.3$. Figure 2 (b) shows a bifurcation in the momentum along the minor axis of polarization as ellipticity increases. This bifurcation can be explained as resulting from the interaction of the drift momentum of the electron and the Coulomb correction. The value of the bifurcation was shown analytically to approximately coincide with the point where the drift velocity cancels the Coulomb correction [4].

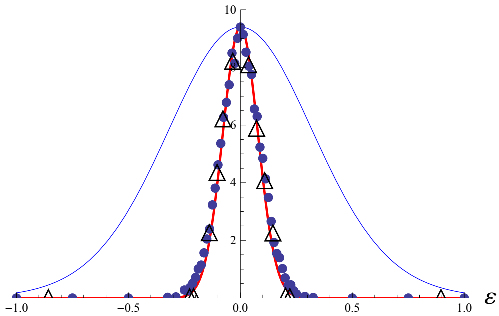

Fig. 1. Analytic curve (line), simulations (•) and experimental data (△) for the Rydberg yield. Total ion yield of He^+, given by P_0, is shown on the same plot (isolated line) . Experimental data is taken from [3]. $\tau_p = 30fs$, $\omega = 0.056$ a.u., Intensity = $1PW/cm^2$

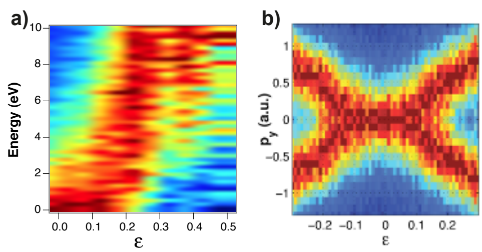

Fig. 2. Energy of electrons observed at the detector as a function of ϵ. b) Corresponding momentum, p_y along the minor axis of polarization. $\tau_p = 33fs$, $\lambda_0 = 788nm$, Intensity = $0.8PW/cm^2$.

2.3 Discussion

In conclusion, we analyzed the dependence of Rydberg states on laser ellipticity, deriving a Gaussian probability distribution for the yield of neutral Rydberg atoms as a function of ϵ; this puts recent experimental and numerical results into a theoretical framework. In particular, our work suggests that rescattering does not play a significant role in the creation of excited neutrals, in contradiction to the mechanism proposed in [3].

The experimental data presented here confirms the theoretical prediction of disappearance of Rydberg states for $\epsilon > 0.3$ by measuring zero energy states at the detector. These states can be considered as a cut-off for the creation of bound trajectories since they correspond to asymptotically large values of n (the quantum number of the Rydberg state).

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