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l-DISTRIBUTIONS OF THE FIRST ELECTRON TRANSFERRED TO MULTIPLY CHARGED IONS INTERACTING WITH SOLID SURFACES

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Abstract. We analyze the angular momentum distributions of the electron transferred into the Rydberg states of multiply charged ions escaping the solid surfaces. The population probabilities are calculated within the framework of two-state-vector model; in the case of large values of the angular momentum quantum numbers l the model takes into account an importance of a wide space region around the projectile trajectory. The reionization of the previously populated states is also taken into account. The corresponding ionization rates are obtained by the appropriate etalon equation method; in the large-l case the radial electronic coordinate ρ is treated as variational parameter. The theoretical predictions based on the proposed population-reionization mechanism fit the available beam-foil experimental data; the obtained large-l distributions are also used to elucidate the recent experimental data concerning the multiply charged Rydberg ions interacting with micro-capillary foil.

1. INTRODUCTION

For a long time it is known that the Rydberg states of multiply charged Rydberg ions can be populated during the interaction with conducting solid surface. The beam-foil type of experiments, see, e.g. Veje et al. (1985, 1988), and Bashkin et al. (1982), performed at intermediate velocities ($v \approx 1$ a.u.) of the ionic projectiles SVI, ClVII and ArVIII, provide non-linear electron capture probability distributions for both principal and angular momentum quantum numbers, n and l, of the final bound states (n, l, m). Recently, a new type of experiment by Morishita et al. (2004) produced an evidence about the l distributions in the large-l region, for the ions Ar^{7+} and Ar^{8+} at velocities $v \approx 0.2$ a.u. interacting with micro-capillary foil.

The probability distributions P_{nl} for the low-l Rydberg states ($l = 0, 1$ and 2) have been obtained theoretically within the framework of two-state-vector model (TVM) by Nedeljković et al. (1994) and Nedeljković and Nedeljković (1998). The model has been extended to the case of large-l Rydberg states ($l \geq 3$) by Nedeljković et al. (2003). In both cases the reionization was neglected. Effects of reionization in the low-l case have been included in the population process by Nedeljković and Nedeljković (2003); the ionization was considered as a decay process, and the etalon equation method (EEM) was proposed for solving the complex energy eigenvalue problem.

In this paper we include the reionization in the large l region. Just in this region, and for higher n values, the absence of the experimental data in the beam-foil geometry has been previously considered as the existence of the thresholds at $l = l_{thr} < l_{max}$. However, the new experiment with micro-capillary foil gives the nonzero population probabilities in this region. We shall demonstrate that the renormalized probabilities $\bar{P}_{nl}$, obtained by inclusion of reionization in the TVM, reconstruct the entire l distribution of the first electron transferred to the ions in the vicinity of solid surface.

2. RENORMALIZED TVM

We consider the the population-reionization (capture-recapture) process of Rydberg states of multiply charged ions escaping solid surfaces with velocity v. In the large-l case the neutralization process (electron capture from the the solid into the ionic field) can be suppressed by the reionization (electron recapture by the solid). Accordingly, if the reionization is remarkable, only a fraction of the formed Rydberg states survives. The both processes can be incorporated in the two-state vector model.

Applying the TVM, our prime intention has been to learn information about the behavior of the active electron which left the solid surface at the time t_{in}, but which will be detected in the final bound state at the time t_{fin}. To this end, we describe the single active electron simultaneously by two wave functions $\Psi_1(\vec{r}, t)$ and $\Psi_2(\vec{r}, t)$. The state $\Psi_1(\vec{r}, t)$ evolves from an initial state Ψ_{in} labeled by the set of parabolic quantum numbers $\mu_{M,in}$ at the time $t_{in} = 0$. The population process represents a "transition" $\Psi_1(\vec{r}, t) \rightarrow \Psi_2(\vec{r}, t)$ at the intermediate time $t \approx \tau$, due to the "measurement" of the electron localization in the ionic region. If the reionization could be neglected, the state $\Psi_2(\vec{r}, t)$ would evolve into a final bound state determined by the spherical quantum numbers $\nu_{A,fin} = (n, l, m)$ at the time $t_{fin} \rightarrow \infty$. The concept of the mixed flux through a moving Firsov plane S_F, used in the calculation of the two-state amplitude offers the possibility to treat the functions $\Psi_1(\vec{r}, t)$ and $\Psi_2(\vec{r}, t)$ in the "interaction-free" region. Using the appropriate asymptotic forms of wave functions, the final population probabilities P_{nl} have been obtained for both the low-l and the large-l Rydberg states, see Introduction.

The reionization is included in the model by introducing the "renormalized" wave function $\bar{\Psi}_2(\vec{r}, t)$, which represents a decaying state with a decay factor of the following form:

$$\mathcal{E}_{\mu_{A0}}(t) = \exp\left[-\frac{1}{2}\int_{\tau}^{t} \Gamma^{I}_{\mu_{A0}}(t)dt\right], \tag{1}$$

where $\Gamma^{I}_{\mu_{A0}}(t)$ is the reionization rate corresponding to the intermediate parabolic quantum numbers μ_{A0}. The experimentally verifiable renormalized population probability $\bar{P}_{nl}$ is given by

$$\bar{P}_{nl} = \mathcal{E}^2_{\mu_{A0}} P_{nl}, \tag{2}$$

where $\mathcal{E}^2_{\mu_{A0}} = \lim_{t\rightarrow\infty} \mathcal{E}^2_{\mu_{A0}}(t)$, whereas P_{nl} represents the electron capture probability (without reionization) into the final Rydbeg state (n, l, m).

From Eqs. (1) and (2) we see that the problem of reionization is reduced to the calculation of the decay factor $\mathcal{E}_{\mu_{A0}}(t)$, expressed via the ionization rate $\Gamma^{I}_{\mu_{A0}}(t)$. The intermediate parabolic quantum numbers which give the main contribution to the reionization process are determined by the quantum numbers of the most probable populated states: in this interplay of quantum numbers we get that $\mu_{A0} = \{n_1 =$

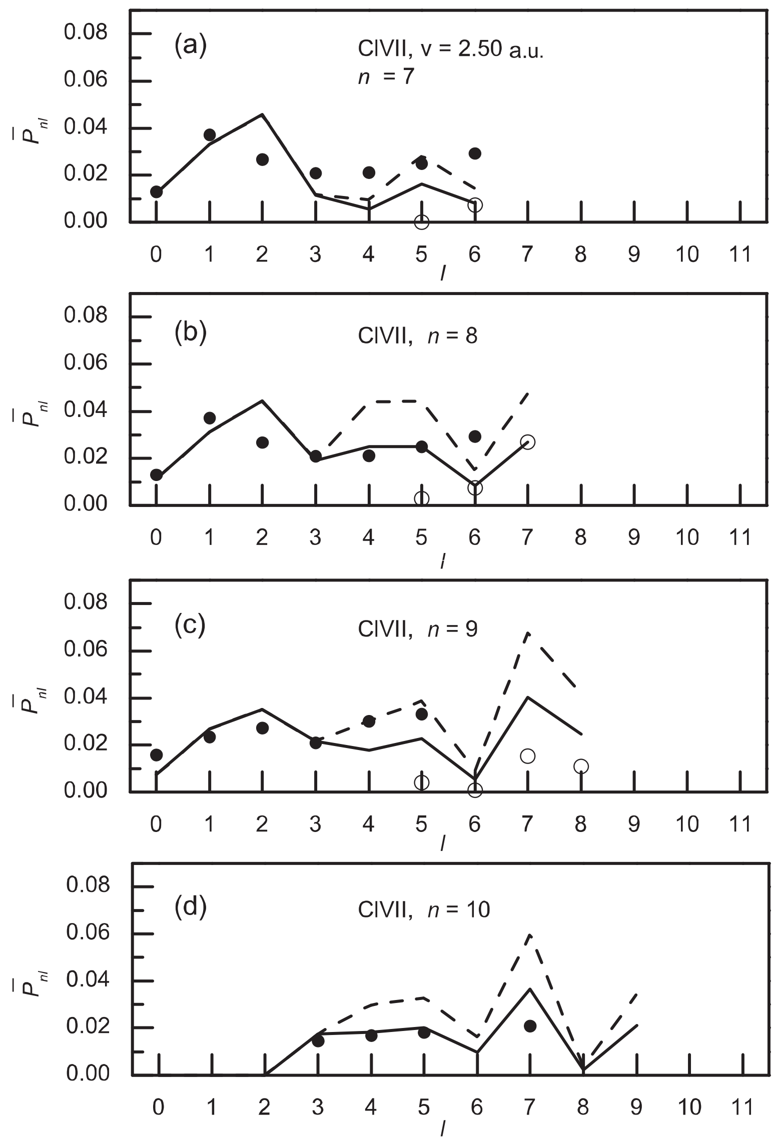

Figure 1: Renormalized population probabilities $\bar{P}_{nl}$ (full curves) and population probabilities P_{nl} (dashed lines) for the ClVII ion, via angular momentum quantum number l, for $7 \leq n \leq 10$ and $v = 2.50$ a.u. The low-l probabilities P_{nl} are obtained by Nedeljković and Nedeljković (1998) and the large-l values P_{nl} are obtained by Nedeljković et al. (2003). Note the existence of the threshold value $n = n_{thr} = 9$ in the low-l region. Dots are the beam-foil experimental data, see, e.g. Veje et al. (1985, 1988); the experimental data obtained in the presence of micro-capillary foil by Morishita et al. (2004), are presented by circles.

$0, n_2 = n-1, m = 0\}$. The ionization rates $\Gamma^I_{\mu_{A0}}(t)$ in the low-l case have been calculated by Nedeljković and Nedeljković (2003). The large-l case was considered by Nedeljković et al. (2008) for the intermediate quantum numbers $\mu_{A0} = \{n_1 \approx (n-1)/2, n_2 \approx (n-1)/2, m = 0\}$ of the Rydberg states of multiply charged ions approaching solid surface; with full analogy with the considered case, one can obtain the rates in the case relevant for the reionization process.

3. RESULTS

The electron exchange during the intermediate stages of the ion-surface interaction results in the final Rydberg system (n, l, m) at $t_{fin} \to \infty$. The experimentally verifiable population probability $\bar{P}_{nl}$, Eq. (2), can be calculated explicitly for all relevant values of the ion-surface parameters.

In Fig. 1, we present the l-distributions of the probabilities P_{nl} and $\bar{P}_{nl}$ for $n = 7-10$ of the ClVII ion ($Z = 7$) escaping the solid surface with the velocity $v = 2.50$ a.u. The population probabilities P_{nl} are presented by dashed curves; the renormalized population probabilities $\bar{P}_{nl}$ obtained by inclusion of reionization are presented by full lines. The low-l probabilities ($l = 0, 1$ and 2) are obtained by Nedeljković and Nedeljković (1998); the probabilities P_{nl} in the large-l case are obtained by Nedeljković et al. (2003). Let us note that, in contrast to the large-l case, the population of the low-l Rydberg states is characterized by the existence of the threshold value of the principal quantum number $n = n_{thr}$, i.e., $\bar{P}_{nl} = 0$ for $n > n_{thr}$.

The properly normalized beam-foil experimental data for the population of the Rydberg levels of ClVII ion, see e.g. Veje et al. (1985, 1988), are presented in Fig. 1 by dots; data are for the ionic velocity $v = 2.50$ a.u. The experimental data for neutralization of the Ar^{7+} ion ($Z = 7$), obtained in the presence of micro-capillary foil by Morishita et al. (2004), are also presented in Fig. 1 (circles). The available experimental data are for $v \approx 0.2$ a.u., so that the experimental results are scaled to the intermediate velocity case (and normalized).

Considering the l distributions presented in Fig. 1 we recognize that the proposed renormalized TVM predictions are in agreement with the both sets of available experimental data. The use of the more accurate l-dependent decay factor $\mathcal{E}^2_{\mu_{A0}}$, as well as the exact scaling factor between the low and the intermediate velocity results, will further improve the presented l-distributions.

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