Trapping of Rydberg atoms in optical lattices

G. Raithel¹, K. C. Younge¹, S. Anderson¹, B. Knuffman²
¹FOCUS Center, Department of Physics, University of Michigan, Ann Arbor, MI 48105
²Center for Nanoscale Science and Technology, National Institute of Standards and Technology, Gaithersburg, MD 20899
graithel@umich.edu

Abstract: We study Rydberg atoms in ponderomotive optical lattices. Unlike for ground-state atoms, for Rydberg atoms in an optical lattice the extent of the electronic wave-function can approach the lattice period. This leads to state-dependent adiabatic trapping potentials that are unique to Rydberg atoms. We first discuss a theoretical model of adiabatic lattice potentials of Rydberg atoms. Then, we use microwave spectroscopy to experimentally demonstrate and investigate the state-dependence of the adiabatic potentials of S₁/₂ Rydberg states of rubidium. The observed microwave spectra depend strongly on both the principal quantum number and the depth of the lattice. A semi-classical simulation is used to explain the features seen in the spectra. Based on the results, we determine the trapping efficiency of the ponderomotive optical lattice.

1. Introduction
The large size of Rydberg atoms results in exaggerated interaction properties that lead into direct applications in quantum computation and high-resolution spectroscopy (see, for instance, [1]). To harness the potential of Rydberg atoms, it is necessary to develop tools suitable to store the atoms at well-defined positions. A promising venue to accomplish this is to use periodic optical lattices in which Rydberg atoms can be localized. The present work marks the first time that two previously separate realms of atomic physics are combined: spatial control of atoms in optical lattices and Rydberg-atom spectroscopy. The experimental and theoretical results presented in this report demonstrate the unusual behavior of Rydberg atoms in optical lattices. The observed characteristics are, in most parts, due to the large ratio of the atom size to the optical-lattice periodicity. The presented work sets the stage for the use of optical lattices as an effective Rydberg-atom trapping device.

2. Lattice potentials
In the first part of the presentation, we discuss a theoretical model of the adiabatic potentials of Rydberg atoms in a one-dimensional optical lattice. A free electron in a rapidly oscillating electric field experiences a ponderomotive energy of \( V_p = \frac{e^2 |E|^2}{4m_0c^2\omega^2} \), where \( e \) and \( m_0 \) are the electron charge and mass, respectively, and \( E \) and \( \omega \) the field amplitude and frequency. In an optical lattice, the ponderomotive potential is spatially periodic and forms a grating from which electrons can be scattered (Kapitza-Dirac effect). Since a Rydberg electron is only weakly bound, its interaction with a superimposed laser field also occurs largely via the ponderomotive potential. This has been confirmed by measuring light shifts of Rydberg atoms in high-intensity laser fields (see, for instance, [2]). Here, we calculate the adiabatic lattice potentials, \( V_{ad}(z) \), of Rb atoms in continuous, one-dimensional standing-wave ponderomotive lattices, taking into account all lattice-induced state-mixing effects [3]. The adiabatic potentials are found to exhibit a rich, level-dependent structure, as seen in the example shown in Figure 1. In the report, we interpret the observed structures using an effective-fields model as well as semi-classical concepts.

Fig. 1: Calculated adiabatic lattice potentials of Rb Rydberg atoms in units of wavenumbers vs position in the lattice. The ponderomotive optical lattice has a laser wavelength of 1064nm and a peak ponderomotive shift of 2GHz. The atoms have a principal quantum number \( n=65 \) and magnetic quantum number \( m_f=2.5 \).
3. Spectroscopy of Rydberg atoms in a ponderomotive optical lattice

For the simplified case of non-degenerate Rydberg levels, considered in the presented experimental work, state mixing is negligible, and the adiabatic lattice potentials, $V_{\text{ad}}(\mathbf{R})$, simplify to the ponderomotive potential averaged over the atom with a weighting function identical to $\psi$:

$$V_{\text{ad}}(\mathbf{R}) = \int d^3r V_0 (r + \mathbf{R}) |\psi (r)|^2$$

Here, $\mathbf{R}$ is the center of mass coordinate of the atom, $\mathbf{r}$ is the relative coordinate of the Rydberg electron, and $\psi$ is the Rydberg wave-function. If the field varies substantially over a length scale comparable to the size of the atom, $V_{\text{ad}}(\mathbf{R})$ strongly depends on the atomic state, leading to state-dependent ponderomotive shifts of the Rydberg level energies.

In the present experiment [4], we use S-state Rydberg atoms with principal quantum numbers near $n=50$ in a one-dimensional lattice with lattice period $\lambda/2 = 532$ nm. In this case, the atom-size-induced averaging effect increases with increasing $n$. To demonstrate and characterize this behavior, we have measured two-photon microwave spectra of $nS \rightarrow (n+1)S$ transitions of Rydberg atoms located in the lattice. The lattice-induced microwave shifts vary dependent on where the atoms are located in the lattice. Three limiting cases can be clearly distinguished: The shift is positive for Rydberg atoms located near a lattice minimum, negative for atoms located near a lattice maximum, and negative but close to zero for atoms that travel over many wells during the atom-microwave interaction time. These three cases correspond to the three main features observed in the microwave spectra displayed in Figure 2, which are taken for the indicated values of the lattice depths.

In additional work, we have taken microwave spectra for initial principal quantum numbers of $n=62$ and $n=68$. There, the lattice-induced shifts are found to be about half of those seen in Fig. 2 and about zero, respectively. These observations are in close agreement with our calculations of the adiabatic potentials for the respective atomic levels. To obtain a quantitative understanding of the microwave spectra, we employ a semi-classical model in which the center-of-mass atom motion is treated classically while the internal-state dynamics driven by the microwave field is treated quantum-mechanically. The simulated spectra are in close agreement with measured ones (see Figure 2) and allow us to estimate the fraction of Rydberg atoms trapped in the lattice.

In ongoing work we study strategies to improve the trapping efficiency. We use a combination of experimental optimization methods as well as conceptual studies based on the mentioned semi-classical simulation method. We are confident that near-100% trapping efficiency can be achieved. The presentation will conclude with a report on the present state of this effort.

4. References