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Cold Rydberg atoms: few body effects and high order interaction

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14. ABSTRACT
In this report, we have focused our attention to the lifetime measurements involving nS and nD states, which were presented in the previous report. We have observed that there was a discrepancy between theory and experiment performed at T=300 K. We have developed a theoretical model, which considers the finite size of the vacuum chamber. Such effect modifies the spectrum of the blackbody theory, reducing its influence, and therefore increasing the lifetime. Such observation may be important where a larger lifetime is desired, but the use of cryogenic techniques is not possible. We have also investigated the excitation of Rydberg states using Laguerre-Gauss laser beams in dipole prohibited transition. In particular, we are interested in transitions from the 5P3/2 to the nP Rydberg state. We believe that we could not observed them due to the low density/volume of the sample.

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Cold Rydberg atoms: few body effects and high order interaction

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Objective: The main goal in this research is to investigate anisotropy in an optical dipole trap, specially using spatial microstructures. We also plan to investigate a few-body Förster resonance and a dipole-quadrupole interaction.

Abstract: In this report, we have focused our attention to the lifetime measurements involving nS and nD states, which were presented in the previous report. We have observed that there was a discrepancy between theory and experiment performed at T=300 K. We have developed a theoretical model, which considers the finite size of the vacuum chamber. Such effect modifies the spectrum of the blackbody theory, reducing its influence, and therefore increasing the lifetime. Such observation may be important where a larger lifetime is desired, but the use of cryogenic techniques is not possible. We have also investigated the excitation of Rydberg states using Laguerre-Gauss laser beams in dipole prohibited transition. In particular, we are interested in transitions from the $5P_{3/2}$ to the nP Rydberg state. We believe that we could not observed them due to the low density/volume of the sample.

I. Introduction

For the last 15 years, we have been witnessing amazing surprises in the field of cold Rydberg atoms mainly due to the long-range nature of the interactions and the exaggerated properties of highly excited atoms. Some of such surprises has been possible thanks to the development of high-density atomic sample held in an optical dipole trap. In this last report, we have focused our attention to the lifetime measurements involving nS and nD states, which were presented in the previous report. We have observed that there was a discrepancy between theory and experiment performed at T=300 K. In order to explain such discrepancy, we have developed a theoretical model, which considers the finite size of the vacuum chamber. Such effect modifies the spectrum of the blackbody theory, reducing its influence, and therefore increasing the lifetime. Such observation may be important where a larger lifetime is desired, but the use of cryogenic techniques is not possible. Some examples could be quantum computation, quantum sensoring, etc. In this last year, we have also investigated the excitation of Rydberg states using Laguerre-Gauss laser beams in dipole prohibited transition. In particular, we are interested in transitions from the 5P3/2 to the nP Rydberg state. We believe that we could not observed them due to the low density/volume of the sample. In this report, we explain both experiments in more details.

I.1. Experiments

In the last report, we present the lifetime measurement for the nS and nD states. A more careful analysis has showed a discrepancy between the results and the experimental data. In fact, there was a wrong constant in the lifetime fitting procedure. In Fig. 1, we show our experimental data and the theoretical curves. The theoretical curves are plotted for two temperatures (T = 0 and 300 K) and two theoretical models [1.2]

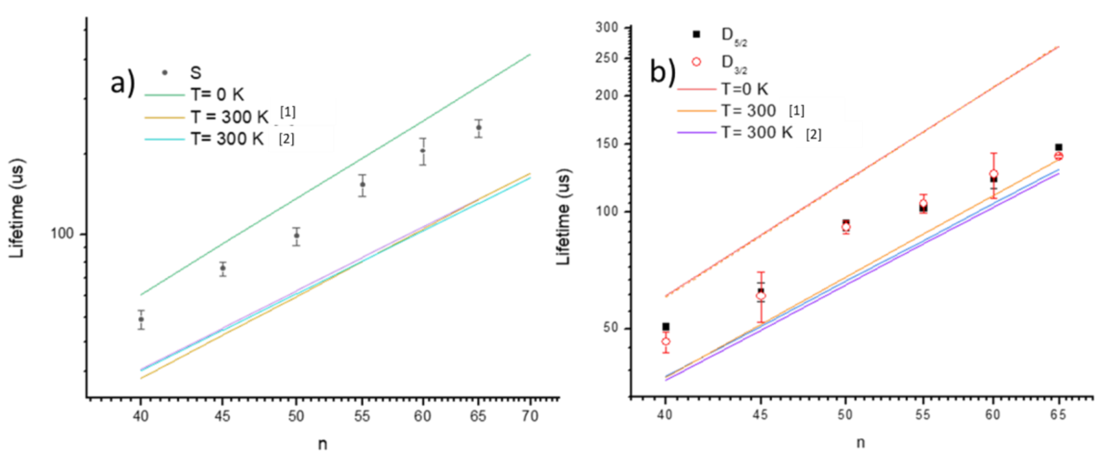

FIG. 1. Lifetime measurements states a) nS and b) $nD_{3/2}$ and $nd_{5/2}$. The theoretical curves are for two distinct temperatures (T = 0 and 300 K) and two theoretical models [3.4].

These results were presented at the Third International Workshop on Rydberg Physics, which I organized in Recife in December 2018. We hoped that some researcher could help us to understand such data. In reality, Dr. Löw, from Sturgard University, warned us the fact that small metal chambers, where the MOT is formed, can modify a Rydberg state lifetime. In addition, Professor Shaffman, from University of Wisconsin, warned us that the university WiFi network could interfere with the measurement.

So we have decided to make a model that considers the finite size of the cavity. If the radiation of the black body due to a finite temperature is considered, an excited atom can decay stimulated transitions to other states and its lifetime is modified to an effective life time τ_{eff}, which is given by the sum of the decay rate at Kelvin zero Γ_{esp} and the black body transition rate γ_{BB}:

$$\tau_{eff}{}^{-1} = \Gamma_0 = \Gamma_{esp} + \Gamma_{BB}$$

The calculation of the black body transition rate takes into account the lower and upper states:

$$\Gamma_{BB} = \sum_{n'} N_{nn'} * A_{n \to n'}$$

Where, $N_{nn'}$ is the number of photons with frequency $\omega_{nn'}$ at a temperature T as follows:

$$N_{nn'} = \frac{1}{exp\left(\frac{\hbar\omega_{nn'}}{k_B T}\right) - 1}$$

To include the effect of a finite size cavity, each term of the sum in the above equation is weighted by a factor $\gamma_{nn'}$, which represents all the relevant spatial modes almost resonant to the atomic transition that fit the cavity. We enumerated the cavity modes with the index i and defined the resonance condition as the frequency range $|\omega_{nn'} - \omega_i| < \Delta\omega$,where ω_i is the frequency of the i-th mode and $\Delta\omega$ is the linewidth. The frequency of ω_i mode is obtained from the geometry of the cavity and, for a parallelepipedic box, has the value

$$\omega_i = \pi\, c \sqrt{\left(\frac{i_x}{L_x}\right)^2 + \left(\frac{i_y}{L_y}\right)^2 + \left(\frac{i_z}{L_z}\right)^2}$$

L_x is the length of the box and the integer i_x is the index of the mode, both in the x direction; similar variables are defined for the Y and Z directions. Keeping that in mind, the factor γ_{nn} can be written as:

$$\gamma_{nn'} = \frac{1}{i_{max}} \sum_{|\omega_{nn'} - \omega_i| < \Delta\omega} f_{Airy}\left(i_{x,y,z}\right)$$

where i_{Max} is the total number of cavity modes and F_{airy} represents the Airy function for the i-th cavity mode in the X, Y, Z directions. BB's contribution to an atom within the cavity is given by:

$$\Gamma_{BB} = \sum_{n'} \gamma_{nn'} N_{nn'} * A_{n \to n'}$$

In Fig. 2, we show the results for the nS and nD states. For the nS states (Fig. 2a), the result is very good for a reflectivity of R = 90%, for the actual dimensions of our vacuum chamber. Of course, the reflectivity of stainless steel is high, especially in the microwave regime, where most of the terms contribute to the state lifetime. But since there are several windows for optical access, the effective reflectivity turns to be smaller. Anyway, the final result is in good agreement with the experimental data. However, if we apply the same model to the nD state (Fig. 2b), considering R = 90%, the result is not so good. As we increase the quantum number, n, the model does not predict the measured result. In fact, the experimental points are below the theoretical curve. We believe that is due to the fact that in the case of nD states, the energy splitting between adjacent states is smaller than in the nS states. And so they are more influenced by the university WiFi network. We have tried to implement a model, considering the influence of WiFi, but without success. For the future, we intend to perform a measurement where we can control the power of WiFi (5 GHz), present in the experiment. This should explain such measurement. We should point out two important facts about our model: i) if we do the factor $\gamma_{nn'} = 1$ for T = 0 K and 300 K, we reproduce the results of the references [1, 2]. This ensures that the model is correct. Ii) If we make R = 100% for T = 300K, the result is equal to that obtained for $\gamma_{nn'} = 1$ for t = 0 k; and if we make R = 0% for t = 300k, the result is equal to that obtained for $\gamma_{nn'} = 1$ to t = 300 K. That makes sense, because if the T = 300 K, the cavity has high reflectivity, the field modes will not be resonant with the atom, so these can't exchange photons. If the cavity has a low reflectivity, it can accept any photon. This behavior guarantees that the model is correct. We should also emphasize that this result can be interesting for systems where longer lifetime is desired, but it does not require the use of cryogenic techniques. Some examples are quantum computation, quantum sensoring, etc.

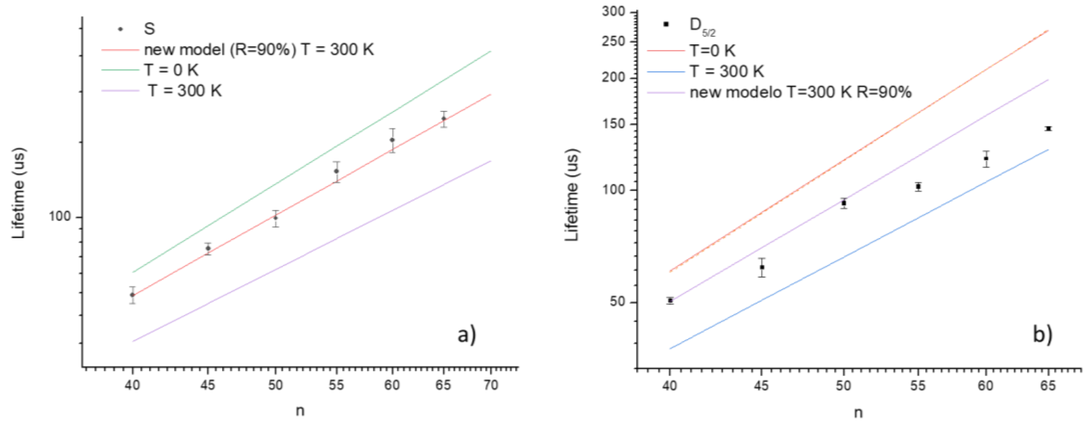

FIG. 2 – Comparison experimental data and theoretical model, which considers the finite size of the vacuum chamber. Lifetime for states a) nS and b) n$D_{5/2}$. The deviation in the nD state must be associated with the influence of university WiFi network.

As mentioned in the previous report, we are interested in Förster resonances involving 03 and 04 atoms. One process can involve nF states, which are dipole prohibit transition from the $5P_{3/2}$ state. We have tried to observe it, however, we were unable to. In order to increase the probability of such process, we have demonstrated theoretical that an excitation performed by a Laguerre-Gauss beam can break the selection rule, making the transition as intense as a dipole allowed [3]. To perform the experiment using a Laguerre-Gauss beam, we have modified our experimental setup in order to allow the excitations laser beams to be perpendicular between themselves and with an dc electric field. In this new configuration, we were able to define exactly the direction of the electric field, besides, we were able to focus the 480 nm laser beam to approximately 10 μm. In one hand, focusing to such small waist is important because the theory of developed for such condition. On the other hand, it reduces the sample volume and therefore the signal. The LG mode, at 480 nm, is created by using a special waveplate retarder from Thorlabs plate, which controls by wave front. In Fig. 3, we show the LG beam intensity profile.

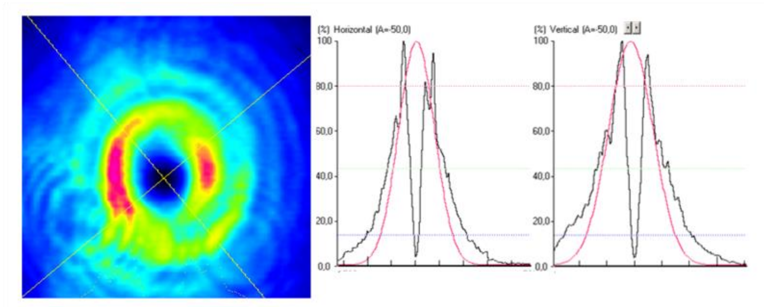

Fig. 3 – LG profile generated in the 480 nm beam.

In order to assure that the LG excitation is working, we tried to excite the nP Rydberg state from the $5P_{/32}$. Such transition are dipole prohibited, however a DC electric field can break this selection rule. We can use this in our advantage, by performing a Stark map measurement, which allows us to assure that we are exciting the nP state in the presence of a static electric field. Of course, that at zero field there should be no excitation. However, if the LG excitation is working, we should observe a no zero nP population at zero field. In Fig. 4, we show the Stark maps obtained for a Gaussian and a LG beams for the 40P state, respectively. Unfortunately, we were unable to observe any increase in the population for zero field compared to the Gaussian beam excitation.

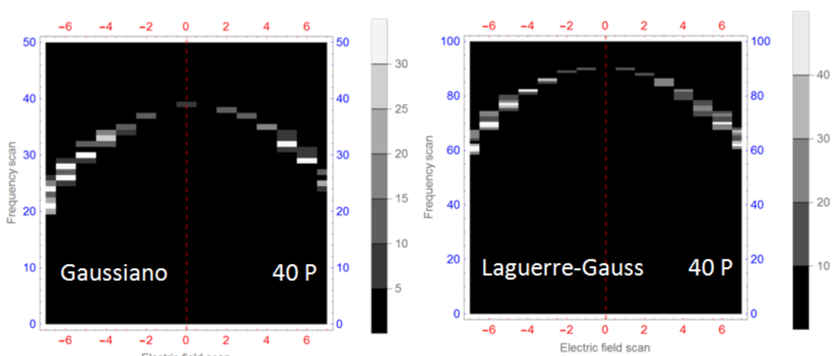

Fig. 4 - Example of Stark maps for 40P state using Gaussian beam and Laguerre-Gauss beam excitation. The selection rule should be broken for the LG beam at zero field.

It is still unclear to us, the lack of signal at zero field for the LG excitation. One possible explanation if the fact that since the LG beam is focused to 10 μm, the volume is small and therefore the signal. However, in order to test this hypothesis, we need to implement an optical dipole trap. Since, our 2DMOT is operating again, we will use it to load the 3D MOT and optical dipole trap.

Personnel Supported

List of personnel associated with the research:

Prof. Dr. Luis Gustavo Marcassa

Dr. Barbara Magnani

Dr. Cristian Mojica

Publications and Conferences

1. Angular Dependence of Rydberg Atom Pair Interactions in a Blockaded Rb Gas – Akbar J. Jozani, James P. Shaffer, Luis F. Gonçalves, and Luis G Marcassa, oral presentation at Third International Workshop on Ultracold Rydberg Physics, Recife, Brasil (2018).
2. Lifetime measurement of nS, nD3/2 and nD5/2 Rb Rydberg states - Cristian A. Mojica Casique, Barbara F. Magnani, Luis G. Marcassa, oral presentation at Third International Workshop on Ultracold Rydberg Physics, Recife, Brasil (2018).
3. Akbar Jahangiri, James P. Shaffer, Luis F. Gonçalves, and Luis G. Marcassa, The Effect of Radially Dependent Polarizability on Rydberg Atom Blockade, accepted at Journal of Physics B (2019).
4. João D. Rodrigues, Luis F. Gonçalves, Hugo Terças, Luis G. Marcassa, and José T. Mendonça, Dynamics and Emergence of Roton Minima in Strongly Interacting Rydberg Gases, PHYSICAL REVIEW A 98, 062713 (2018)
5. Finite size cavity effect on Rubidium Rydberg state lifetimes. BARBARA F. MAGNANI, CRISTIAN A. MOJICA CASIQUE, LUIS G. MARCASSA, submitted to Journal of Physics B (2019).

References

1. Constantine E. Theodosiou, Phys. Rev. A 30, 2881 (1984).
2. I. I. Beterov, I. I. Ryabtsev, D. B. Tretyakov, and V. M. Entin, Phys. Rev. A 79, 052504 (2009). W. Cooke and T. Gallagher, Phys. Rev. A 21, 588 (1980).
3. Joao Rodrigues, L G. Marcassa, and J Mendonca. Journal of Physics B: Atomic, Molecular and Optical Physics, 49, 12 (2015).

São Carlos, 28/September/2019

Prof. Dr. Luis Gustavo Marcassa