Delayed collisional ionization of ultracold Rydberg gas.

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WILEY-VCH Verlag Berlin GmbH
August 22, 2002

We investigate properties of ultracold Rb Rydberg atoms. Electrostatic interactions between Rydberg atoms are much stronger than between normal atoms. Rydberg atoms can even form long range Rydberg molecules. Strong dipole-dipole interactions between Rydberg atoms might find application in quantum computing[1].

In our experiment Rb atoms are first loaded to a MOT at the temperature of 300 μK. The ions formed in a MOT are detected with TOF spectrometer[2] on MCP detector. Significant fraction of Rb atoms in a MOT is in excited $5p_{3/2}$ $(F = 3)$ state. We pump this state to high principal quantum number Rydberg states $(n = 20 - 60)$ with the excimer pumped dye laser. Dye laser operates at the wavelength of 480 nm with the typical pulse energy of 100 μJ while duration of the laser pulse is 15 ns and the frequency bandwidth of 0.15 cm^{-1}. Since the initial state is $5p_{3/2}$ we expect to excite ns and nd Rydberg states. We first measured the Rydberg series in a MOT and compared the spectra with the tabulated [3] energy levels of Rb. Fig. 1 shows measured frequency spectra at three different arrangements together with the timing sequence for Rb^+ ion detection.

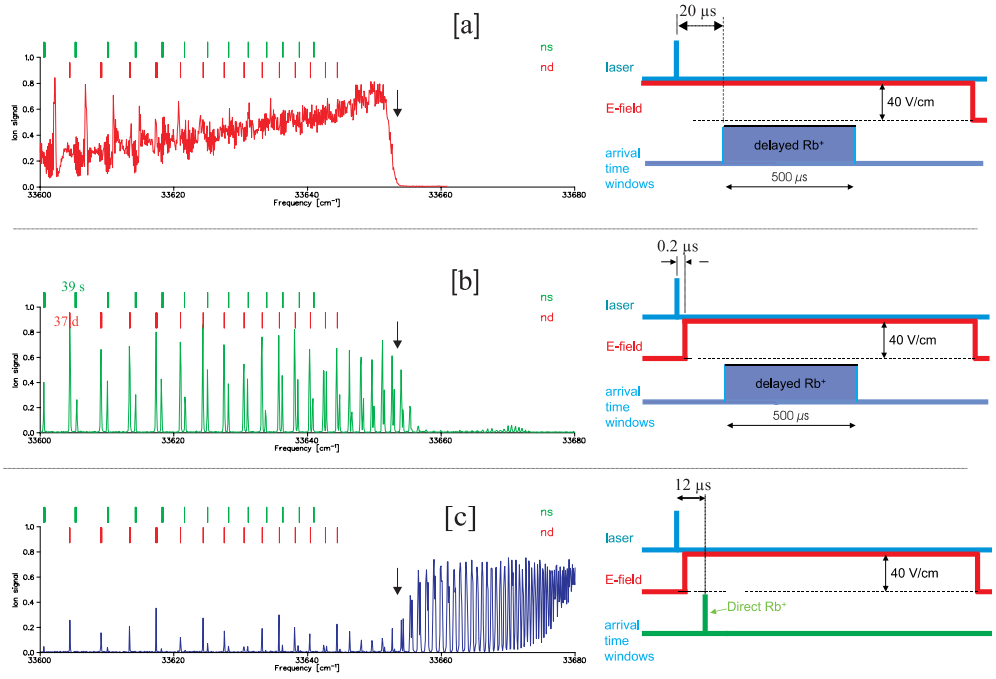

Figure 1: Rydberg spectra of Rb atoms loaded in a MOT measured with three different timing schemes. Vertical arrow marks the field ionization threshold.

In a first case, shown in Fig. 1 [a], the extraction electric field of 40 $\frac{V}{cm}$ is applied during the excitation with the pulsed dye laser. We detect the ions in a time window 500 μs wide and shifted by 20 μs relative to the excitation dye laser pulse.

In a second case, shown in Fig. 1 [b], we switch the electric field on 200 ns after the laser pulse.

In the third case, shown in Fig. 1 [c], we detect the ions in a time window 1 μs wide and delayed by the time of flight of Rb^+ ions which is 12 μs.

In a first case, Fig. 1 [a], we observed number of stark states due to influence of the external electrical field. The sharp edge in the spectrum corresponds to the field ionization threshold which is in our case located 38 cm^{-1} below the ionization threshold of Rb.

In a second case, Fig. 1 [b], we see only ns and nd Rydberg states. The edge corresponding to the field ionization threshold also appears. Measured energy levels are compared with the tabulated levels as indicated with the markers above the spectrum. We didn't observe any significant frequency line shifts in a MOT compared to the tabulated values within experimental accuracy of ± 0.2 cm^{-1}.

In a third case, Fig. 1 [c], we see significant increase of the ion signal above the field ionization threshold. By comparing Fig. 1 [b] and [c] we conclude that the ion signal appearing in the spectral range below the field ionization threshold in Fig. 1[b] must be due to collisional ionization processes delayed with respect to field ionization. The efficiency of field ionization is nearly 100% since the ion signal in Fig. 1 [a] and [b] dropped almost to zero above the field ionization threshold.

We then excited specific Rydberg state, $40d$, and measured temporal appearence of ion signal. Temporal appearence of delayed ionization is shown in Fig. 2 for two different timing schemes. The y axis in Fig. 2 is in logarithmic scale.

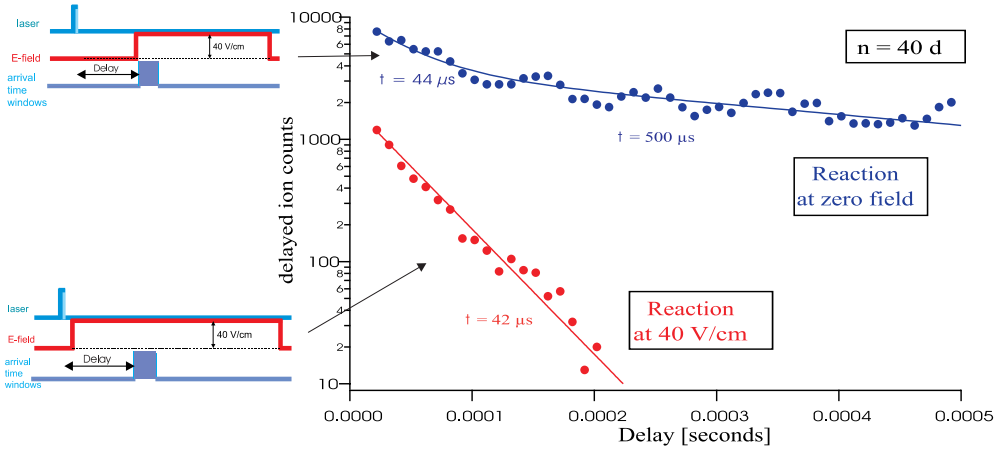

Figure 2: Temporal appearence of delayed ionization for two timing schemes.

In a first case we shift the delay of the electric field together with the detection window relative to the excitation laser pulse. Detected signal as a function of time delay is also shown in Fig. 2 fitted with the upper curve. Slow decay has a decay constant of 0.5 ms.

If we however shift the delay of detection window only, shown in Fig. 2 with lower curve, the decay is much faster with time constant of 40 μs corresponding most likely to the radiative lifetime of $40d$ state.

We can conclude that the lifetime of ultracold Rydberg gas is significantly longer then the radiative lifetime of initially excited Rydberg atoms. This can be explained if we consider

collisions between two Rydberg atoms.

$$Rb(nd) + Rb(nd) \rightarrow Rb(n'l') + Rb(n"l") \tag{1}$$

In reaction expressed by Eq. 1 Rydberg atoms initially excited to $40d$ state can be redistributed into higher principal quantum number Rydberg states $Rb(n"l")$ with high angular momentum $l"$. These states might be long lived[4].

Another possible reaction can be conversion of Rydberg gas to ultracold plasma[5, 6] expressed by Eq. 2.

$$Rb(nd) + Rb(nd) \rightarrow Rb(n'l') + Rb^{+} + e^{-} \tag{2}$$

This ultracold plasma contains electrons and ions with very low kinetic energy. Low kinetic energy electrons are attracted by the cold Rb^{+} ions and thus make a long lived system.

To distinguish between these two possible mechanisms of delayed ionization the height of the extraction electrical field have to be varied as we plan in our future work.

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