Recombination during expansion of ultracold plasma*

Zhao Jian-Ming(赵建明)†, Zhang Lin-Jie(张临杰), Feng Zhi-Gang(冯志刚), Li Chang-Yong(李昌勇), and Jia Suo-Tang(贾锁堂)

State Key Laboratory of Quantum Optics and Quantum Optics Devices, College of Physics and Electronics Engineering, Shanxi University, Taiyuan 030006, *China*

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Signals of ultracold plasma are observed by two-photon ionization of laser-cooled caesium atoms in a magneto-optical trap. Recombination of ions and electrons into Rydberg atoms during the expansion of ultracold plasma is investigated by using state-selective field ionization spectroscopy. The dependences of recombination on initial electron temperature (1–70 K) and initial ion density ($\sim 10^{10}$ cm^{-3}) are investigated. The measured dependence on initial ion density is $N^{1.547\pm0.004}$ at a delay time of 5 μs. The recombination rate rapidly declines as initial electron temperature increases when delay time is increased. The distributions of Rydberg atoms on different values of principal quantum number n, i.e. n = 30–60, at an initial electron temperature of 3.3 K are also investigated. The main experimental results are approximately explained by the three-body recombination theory.

Keywords: recombination, ultracold plasma, Rydberg atoms

PACC: 3280P, 3150, 3280F

1. Introduction

Ultracold plasma can be obtained by the ionization of laser cooled and trapped atoms or the evolution from cold Rydberg atoms.[1,2] Ultracold plasma formed in a magneto-optical trap (MOT) is unconfined and expands into the surrounding vacuum on a time scale of about 10 μs. The expansion mechanism is complicated, and the expansion process of plasma was investigated by using the excitation of electron plasma oscillations,[3] optical probes,[4] electron heating mechanisms,[5] the recombination of plasma into Rydberg atoms,[6] and so on. The ultracold plasma also presents a challenge to theory. The expansion of ultracold plasmas was investigated by using the molecular-dynamics method and the evolution of electron temperature using a Monte Carlo calculation.[7−10]

Recombination of electrons and ions into Rydberg atoms is a fundamental process in plasma physics. Killian *et al.*[6] obtained the signals of Rydberg atoms in the expansion of xenon plasma by recombination at electron temperatures of 1–1000 K and ion densities of 10^5–10^{10} cm^{-3} and investigated the three-body recombination mechanism, and also studied the evolution of electron temperature during the expansion. Cummings *et al.*[11] obtained information about the expanding process of strongly coupled calcium plasma by fluorescence measurements. Simien *et al.*[4] and Chen *et al.*[12] studied the ion dynamics of ultracold strontium plasma by absorption imaging and equilibration of strongly coupled ions. Recently Zhang *et al.*[13] measured the expansion of ultracold plasma across the field lines of a uniform magnetic field and observed the expansion velocity to be scaled as $B^{-1/2}$.

In a conventional plasma expansion process the recombination of electrons and ions takes place by three different reaction mechanisms, radiative recombination (RR), dielectronic recombination (DR), and three-body recombination (TBR). However, TBR is an important process in ultracold plasma. In TBR, an ion and two electrons collide to form an energetic electron and a highly excited Rydberg atom. The TBR rate has dependence on electron temperature, $T^{-9/2}$,[14] at 1000 K or more. Hahn[15] improved the TBR rate further by adopting a simple correctional procedure in terms of a density-dependent cutoff of these high Rydberg atoms and obtained that the TBR total rate coefficients were proportional to T^{-1} under the condition of low temperature and strong cou-

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†Corresponding author. E-mail: zhaojm@sxu.edu.cn

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pling. Recently the results have shown that three-body recombination and its associated heating play a critical role in the evolution of ultra-cold plasma, the early-time Te measurements and simulations suggest that the electrons remain weakly coupled due to the heating process during the ultracold plasma expansion so that traditional three-body theory is still valid. For the fundamental interest in TBR at low temperatures, the TBR process is important in the formation of cold anti-hydrogen through positron-antiproton recombination.[16]

In the present work, we use two-photon excitation to ionize laser-cooled caesium atoms in MOT and obtain the ultracold plasma. We obtain signals of Rydberg atoms formed by recombination during the expansion of ultracold plasma, and the recombination rate to be approximately 12%. We vary the power of the pulsed dye laser to change the initial ion density and vary the wavelength of the pulsed dye laser to change the initial electron temperature, so as to investigate the expansion of ultracold plasma. We have measured a dependence on ion density at a delay time of 5 μs, which is $N^{1.547\pm0.004}$. Furthermore, we obtain the distributions of Rydberg atoms on different values of principal quantum number n, i.e. n = 30–60, by using state-selective field ionization.

2. Experiment

The experimental setup has been described in Ref. [17] in detail. Briefly, 1.0×10^7 cold caesium atoms at a typical temperature of 200 μK are prepared in MOT. The spatial distribution of the cloud density is Gaussian with a diameter of ∼600 μm. The cold cloud is located between two parallel metal grids spaced 15 mm apart. We use two-photon excitation to ionize cold caesium atoms, which is shown in Fig. 1(a). The first photon ($\lambda = 852$ nm) from the trapping and cooling laser excites ground state atoms to $6P_{3/2}$ states, while the second photon ($\lambda \sim 508$ nm) from a pulsed dye laser excites $6P_{3/2}$ states to ionization states, thereby forming an ultracold plasma. The pulsed dye laser is pumped by a frequency-tripled pulsed Nd:YAG laser (Spectra-Physics DCR-3). The dye laser pulse is 7 ns in duration with a bandwidth of 0.07 cm^{-1} and wavelength range from 480 nm to 540 nm running at 10 Hz repetition rate. The laser is focused in the centre of the cold cloud by a lens with a waist radius of ~ 150 μm, which is smaller than the size of the cold cloud. We achieve a cigar-shaped ion distribution within the MOT. We apply electric fields between the grids to push the electrons with higher energy or to ionize Rydberg atoms and drive the resulting electrons onto a micro-channel plate (MCP) detector that is located behind one of the grids. The detected signal is processed by a boxcar integrator (SRS-250) and recorded by a computer. The signal is averaged 10 times for reducing the error due to the fluctuation of pulsed dye laser.

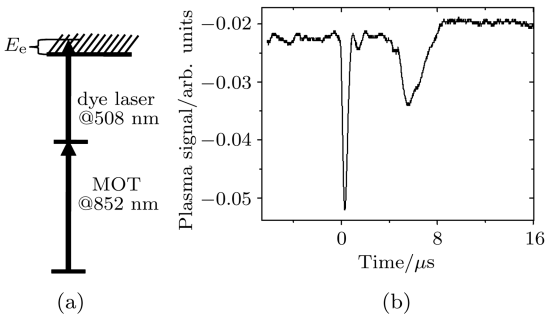


Fig. 1. Relevant caesium atomic energy levels for creating ultracold plasma (a) and signal of ultracold plasma (b).

In the process of photo-ionization, ions and electrons obey momentum and energy conservations. Because the electron-to-ion mass ratio is very small, this leads electrons to take almost the excess energy ΔE between the photon energy and the ionization threshold. The initial electron temperature $T \sim \Delta E/k_B$ is determined by the wavelength of the dye laser, while the ion temperature is nearly equal to the temperature of the cold cloud. The initial electron kinetic energy $E_e \sim \Delta E$ is thus much larger than that of the ions. So the caesium ions can be approximately treated as being at rest initially. We vary the initial electron temperature T by changing the wavelength of the pulsed dye laser and vary the initial ion density by changing the power of the dye laser with neutral attenuation plates, so as to investigate the formation of Rydberg atoms due to recombination during the expansion of ultracold plasma.

In the experiment, an electric field of approximately 30 mV/cm is applied to grids to push electrons with higher energy, thus producing the first sharp peak in the signal shown in Fig. 1(b). The ions are nearly immobile on this timescale and create a Coulomb potential energy well for trapping other electrons with lower energy, thereby forming an ultracold plasma. A few microseconds after dye laser pulse, a ramp field of 1 V/cm is applied and a typical ultracold plasma signal is obtained and shown in Fig. 1(b) as a broad peak.

In order to investigate the recombination of ions and electrons in the expansion process, we apply a pulsed electric field with an amplitude of 750 V/cm at (5–30) μs (the electric field of 30 mV/cm is still on, but the field of 1 V/cm is off) after the dye laser pulse which is used to ionize Rydberg atoms of principal quantum number of more than $n = 33$. About 12% of the initial free ions and electrons recombine on a time scale of 5 μs. From the number of the electrons we can infer the number of Rydberg atoms formed by plasma recombination, and from the field which ionizes the atoms we can construct the distribution of Rydberg atoms for different values of principal quantum number n. The formed Rydberg atoms are mainly populated in high l states, and the interaction between the high n and l states are small:[6] atoms can pass the crossings diabatically without changing states.

3. Results and discussion

In the expansion process of plasma, the TBR is an important mechanism. At electron temperature T, the TBR rate is expressed as[15]

$$\alpha_n = AT^{-1}(1 - \mathrm{e}^{-x_n})N^3 n^6 \Gamma / Z^4 \ \ (\mathrm{cm}^{-3} \cdot \mathrm{s}^{-1}), \quad (1)$$

where $A = 7.2 \times 10^{-31}$; N is the density of electrons or ions, for a neutral plasma, $N = N_\mathrm{e} = N_\mathrm{i}$; n is the principal quantum number; Γ is the Gaunt factor; Z is the ion charge; $x_n = Z^2/n^2T$.

The TBR probability is defined as

$$p_n = \alpha_n / N \ \ (\mathrm{s}^{-1}). \quad (2)$$

The total TBR probability is obtained by integrating Eq. (2) for the individual n

$$P = \int_{n_0}^{n_{\max}} p_n \, \mathrm{d}n, \quad (3)$$

where n_0 and $n_{\max}$ are the minimum and the maximum values of principal quantum numbers of recombination Rydberg atoms. We choose $n_{\max} \approx 1.08 \times 10^4 [N \ (\mathrm{cm}^{-3})]^{-1/6}$,[15] which is the principal quantum number cutoff that is related to the ion density. In experimental conditions there are a few Rydberg atoms of quantum number $n > 60$. So we take the $n_{\max} = 200$ for a density of 10^{10} cm^{-3}.

In our experiment, we detect the recombination of Rydberg atoms at (5–30) μs after laser excitation by using state-selective field ionization spectroscopy. The dye laser wavelength is tuned to 508.2 nm (the ionization threshold is 508.26 nm[18]), and corresponding initial electron temperature is 3.3 K. The excited efficiency of the dye laser is about 20%, then we can obtain the 2×10^6 ions and electrons, and the corresponding density is $N_0 = 1.8 \times 10^{10}$ cm^{-3}. Figure 2 shows the number of Rydberg atoms observed as a function of initial ion density and the inset indicates the TOF signal of Rydberg atoms at an initial ion density of 1.1×10^{10} cm^{-3}. It is clear that the number of recombined Rydberg atoms increases as the dye laser power increases. We assume $N_\mathrm{i} \approx N_\mathrm{e}$, and fit the experimental data to obtain the dependence of the Rydberg atoms on density, i.e. $N^{1.547\pm0.004}$. This result approximately accords with Eq. (2) for the density which is smaller than 1.6×10^{10} cm^{-3}. However, for higher densities of initial ions, the number of Rydberg atoms decreases. For higher densities the plasma expansion is faster than expected for a given electron temperature T, thereby yielding a lower plasma density. Meanwhile the recombined Rydberg atoms populate in the lower principal quantum number state which cannot be turned into ionized states by the electric field.

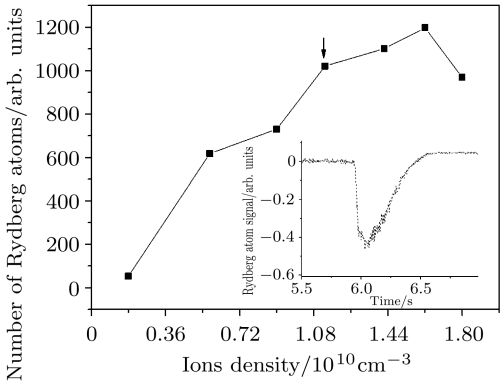


Fig. 2. Number of Rydberg atoms observed as a function of initial ion density, and the dependence of Rydberg atoms on ion density is obtained to be $N^{1.547\pm0.004}$ by fitting the experimental data. Inset is for the TOF spectrum of Rydberg atoms with an initial ion density of 1.1×10^{10} cm^{-3} which is arrowed there.

In order to prove this assumption reasonable, we fix the initial ion density $N = 1.1 \times 10^{10}$ cm^{-3} and change the amplitude of the pulsed electric field that is used to ionize the Rydberg atoms, so as to obtain the distribution of Rydberg atoms for different principal quantum numbers. For a given n state, the ionization field value is expressed as[19]

$$F = F_0/(9n^4), \quad \text{with} \quad F_0 = 5.14 \times 10^9 \ \mathrm{V/cm}. \quad (4)$$

Figure 3(a) shows the recombination probabilities calculated from Eq. (3) for different ranges of principal quantum number with an electron temperature of 3.3 K, and $N_e = N_i = 10^{10}$ cm^{-3}, $\Gamma = 2$. Figure 3(b) shows the Rydberg atom distributions on the quantum number at an initial electron temperature of 3.3 K (squares) and 41 K (circles). The x-axis number is representative of the minimum value n_0 that can be ionized by an applied electric field according to Eq. (4). The experimental results approximately accord with the calculations, which reveals that at a low initial electron temperature three-body recombination takes place at a moderately tight bound level ($n < 50$), and the binding energy of the Rydberg atoms closely matched the excess energy that occurs during the expansion.[6]

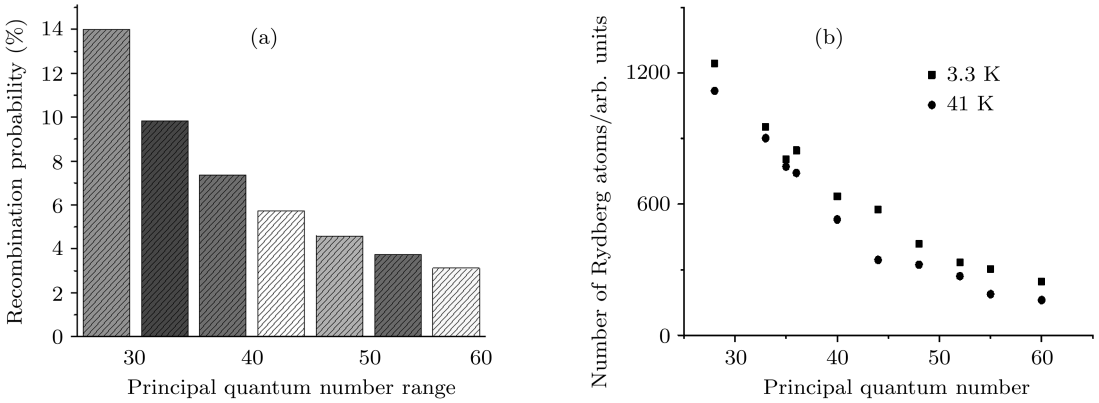


Fig. 3. Recombination probabilities calculated from Eq. (3) for different ranges of quantum number with $N = 10^{10}$, $T_e = 3.3$ K, $Z = 1$, $\Gamma = 2$ (a), and Rydberg atom distributions at two different initial electron temperatures, i.e. 3.3 K (squares), and 41 K (circles) (b). The x-axis number represents the n_0 that can be ionized by an applied electric field.

We further vary the initial electron temperature by changing the dye laser wavelength and fix the initial ion density $N = 1.1 \times 10^{10}$ cm^{-3} and delay time to be 5 μs. The result is shown by the circles in Fig. 4. The number of Rydberg atoms due to recombination decreases slowly as the initial electron temperature increases at a delay time of 5 μs, which is approximately explained with Eq. (3). However, when we increase the delay time up to 30 μs, the number of recombined Rydberg atoms rapidly decreases as the initial electron temperature increases, and the result is shown by the squares in Fig. 4. When the delay time is increased, the time of the interaction between ions and electrons increases. The electron is heated in the expansion process. TBR is an important process during the expansion, in which an ion combines with an electron to form a Rydberg atom while another electron involved is free in the plasma and this extra electron obtains a binding energy as kinetic energy, causing electron temperature to increase. Meanwhile the initial ions in an ultracold plasma are also heated through the disorder-induced heating mechanism. As the ultracold plasma expands, the plasma temperature increases and the ion density decreases specially for higher electron temperatures. Thus the ultracold plasma is confirmed for the high temperature plasma and the recombination rate can be described by the classical three-body recombination theory and the dependence on electron temperature is expressed as $T^{-4.5}$.[10,14]

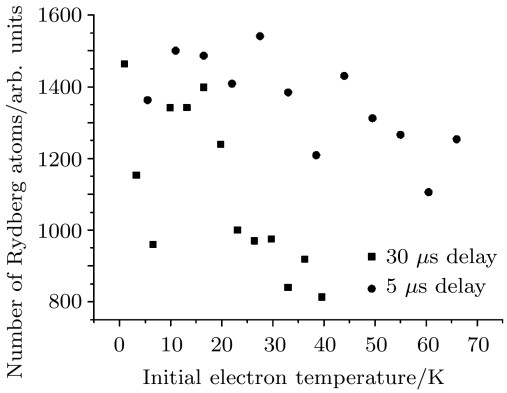


Fig. 4. Number of recombined Rydberg atoms vs. initial electron temperature at delay times of 5 μs (circle) and 30 μs (square). The pulsed electric field is about 800 V/cm which can ionize the Rydberg atoms of principal quantum number $n > 30$ according to the formula of $F = F_0/9n^4$.

4. Conclusion

Formation of Rydberg atoms by recombination in ultracold plasma is observed. The dependences of recombination number of Rydberg atoms on initial electron temperature and ion density are investigated by varying the dye laser wavelength and the laser power. The lower the initial electron temperature and the higher the ion density is, the more Rydberg atoms will form. Rydberg atoms distributions on different principal quantum numbers are also investigated. The results indicate that the recombined Rydberg atoms mainly distribute in a range of $n = 30$–60 in our experimental conditions. The main results are approximately explained by the TBR theory and approximately accord with the results from the TBR model in Ref. [15] under conditions of initial electron temperature $T < 70$ K and initial density about 10^{10} cm^{-3}. As the plasma expands, the electron temperature increases due to three-body recombination and other heating mechanisms, leading the cold plasma to turn into a high temperature plasma.

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