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Measurement of quantum defects of nS and nD states using field ionization spectroscopy in ultracold cesium atoms*

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This paper reports that ultracold atoms are populated into different nS and nD Rydberg states (n=25∼52) by two-photon excitation. The ionization spectrum of an ultracold Rydberg atom is acquired in a cesium magneto-optical trap by using the method of pulse field ionization. This denotes nS and nD states in the ionization spectrum and fits the data of energy levels of different Rydberg states to obtain quantum defects of nS and nD states.

Keywords: ultracold Rydberg atoms, quantum defect, field ionization spectrum, two-photon excitation

PACC: 3280P, 3200, 3580

1. Introduction

Rydberg atoms being populated in the state with a very large principal quantum number n and large dipole interaction ($\propto n^2$) have been extensively studied over many decades.[1] The advanced technology of cooling and trapping of neutral atoms opened up a new research area of ultracold Rydberg atoms which was produced from a small cloud of laser-cooled atoms confined in a magneto-optical trap (MOT).[2−5] Heavy alkali metal atoms for example Rb and Cs are the main components in the investigation of ultracold Rydberg atoms. The accurate energy of Rydberg states of the alkali metal atom is important to the investigation of the interaction between Rydberg atoms including van der Waals interaction, dipole–dipole interaction and manybody collision.[6−13] Because of the large size of the Cs^+ core, the energy of Rydberg states with low angular momenta is below the hydrogenic energy levels. The quantum defects of different low angular momentum states must be considered for calculating the energy of high excited states. Weber and Sansonetti measured the energy of Rydberg states of the neutral cesium atom by using resonantly enhanced two-photon spectroscopy.[14] They gave the energy data of the lower Rydberg states ($n \leq 35$ to nS and nD states) and calculated the quantum defect. But the energy data of higher nS and nD states ($n > 35$) of cesium atoms have not been acquired in the experiment. The energy of the ultracold cesium atom in higher Rydberg states is worth measuring because many interesting dynamic processes occur in ultracold Rydberg gases populated in higher excited states, and the measurement of the quantum defect is valuable for determining the wavefunction of Rydberg states and understanding the properties of the Rydberg atom.

In this work, we obtain the ionization spectrum of higher states of nS and nD ($n = 25 \sim 52$) of ultracold cesium atoms by the method of pulsed field ionization. The ultracold atoms ($\sim$100 μK) in the MOT are excited to Rydberg states by two-photon transition processing. The sequent high voltage pulse ($\leq$25 ns rising and falling time) is applied to ionize the Rydberg atoms. The ion signal is detected by a micro-channel plate detector (MCPD). We obtain the energy data of the states of nS and nD ($n = 25 \sim 52$) and calculate the quantum defects of the nS and nD states by fitting the experimental data.

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2. Experimental setup

The experimental scheme is shown in Fig.1. The Cs ultracold atoms are trapped in the nonmagnetic steel MOT. The cloud of cold atoms has a diameter of $\sim$600 μm, containing 2×10^7 Cs cold atoms with a temperature $T \sim 100\,\mu$K. The cold atoms are excited from the $6S_{1/2}$ state to the $6P_{3/2}$ state by the diode laser (DL100) at first. A green laser beam ($\lambda \sim$510nm) from the pulsed dye laser (PDL-3) excites the atoms from the $6P_{3/2}$ state to nS or nD Rydberg states. The PDL was pumped by the frequency-triple harmonics of a Nd:YAG laser at 355 nm. The DL has a tuning range of 507–540 nm, repetition rate of 10 Hz, 7 ns duration and bandwidth of 0.07 cm^{-1}, respectively. This DL pulse energy in MOT is about 150 μJ to avoid multi-photon ionization of atoms. The cloud of ultracold atoms is midway between two parallel nonmagnetic grids on which high voltage pulse electric fields are applied to ionize Rydberg atoms and drive charged particles to a MCPD behind one of the grids. The high voltage pulse has a maximum of 3.5 kV and 25 ns rising time. The time of flight (TOF) spectra of either ions or electrons could be detected. The signals are sampled by using the Boxcar (SRS250) and recorded by the computer. The digital delay/pulse generator (DG535 SRS) is used to control the timing sequence of DL pulses and pulse electric fields.

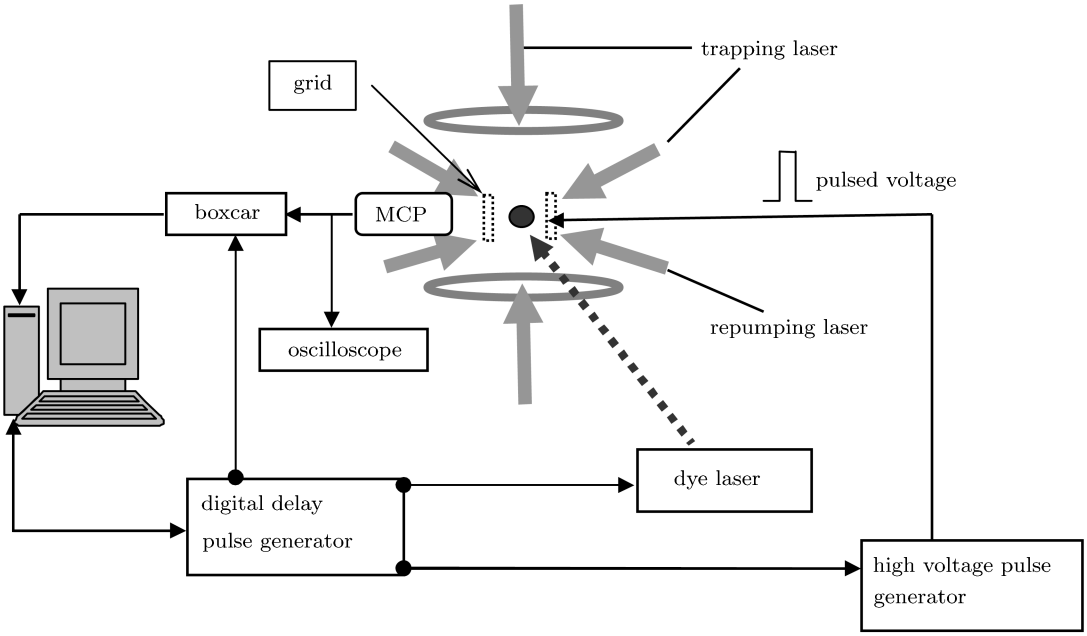


Fig.1. Experimental scheme.

In our experiment, 3.2 kV ionization pulses are applied on the parallel nonmagnetic grids and enough to ionize all $n \geq 25$ Rydberg states. For a state of principal quantum number n, the classical ionization field is: $E_c = 1/16n^4$ (atomic units). The higher voltage pulse can provide bigger acceleration for the ions to impact the MCPD in which the absolute detection efficiency for the ions is proportional to the impact energy of the ions.[15] The ionization pulse is provided at delay times of 50 ns after the DL excitation. Moreover the rise time of the high voltage pulse in our experiment is shorter than 25 ns. These conditions ensure that the ultracold atoms are free of the effect of electric field before ionization. So we neglect the energy level shift produced from the collision between Rydberg atoms and the l-mixing effect in the experiment. The signals of ions from different Rydberg states reach the MCPD at nearly the same time because of high acceleration of the ions and short flight distance. The TOF spectra of ion signals are sampled by a gated integrator with a fixed delay time. Since the shot to shot fluctuations of the DL energy can produce the variation of the signal, we record the average value of 10 samples by the computer in order to improve the signal to noise ratio.

3. Experimental results and analysis

We slowly scan the wavelength of the DL and obtain the ionization spectrum shown in Fig.2. The atoms in the $6P_{3/2}$ state can be only excited to high lying nS or nD state according to the select rules. The intensity of ion signals from nD states is generally stronger than that from the neighbourhood nS states because the transition strengths of nD states are bigger than those of nS states. The interval between nS and nD states decreases as the principal quantum number n increases. When the principal quantum number $n > 55$, the ionization spectrum becomes indistinguishable because of the linewidth of $0.07\,\mathrm{cm}^{-1}$ of DL. We acquire the energy data of the high lying nS and nD states ($n = 25 \sim 52$) and show them in Table 1. Comparing with the data of Ref.[12], we find that our experimental results include the energy data of higher states.

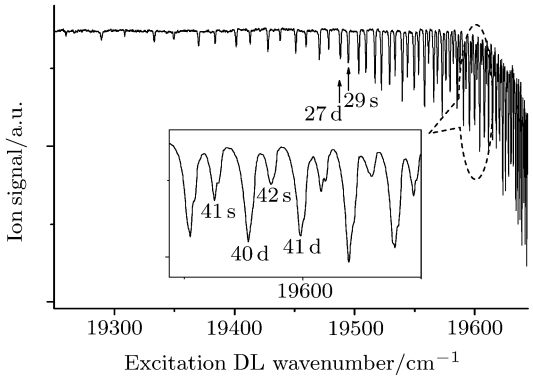


Fig.2. Pulse field ionization spectrum.

Table 1. The energy of nS and nD states. Units are cm^{-1}.

n	nS Ref.[14]	nS [this work]	nD Ref.[14]	nD [this work]
25	31156.44439	31155.5621	31190.35063	31187.7394
26	31178.70760	31178.9427	31208.32704	31206.9531
27	31198.12416	31199.0824		31223.6784
28	31215.15966	31217.1388	31238.15145	31238.2623
29	31230.18805	31232.5517		31251.8914
30	31243.51252	31241.9083	31261.71576	31258.5178
31		31252.8624		31269.3410
32		31263.2634	31280.65687	31279.4678
33		31273.5647		31288.2066
34		31283.0559	31296.10980	31295.8458
35		31291.4474		31303.0253
36		31298.9709	31308.88106	31309.5616
37		31305.8578		31315.6383
38		31312.871		31321.0204
39		31318.1847		31326.1711
40		31323.2196		31330.5695
41		31327.9073		31334.6784
42		31329.6137		31338.961
43		31332.6259		31342.4334
44		31336.4146		31345.6743
45		31340.3510		31348.7415
46		31344.0538		31351.6352
47		31347.2947		31354.2394
48		31350.3041		31356.9305
49		31352.8505		31358.9851
50		31355.5995		31361.3578
51		31358.0881		31362.6727
52		31360.3161		31365.2353

The cesium atom has a big Cs^+ core. To the lowest l states, core penetration of Rydberg electron contributes the main energy depression of nS states and is a short range phenomenon which is described by quantum defect theory.[1] In the higher angular momentum states the Rydberg electron is classically excluded from the core by the centrifugal potential, and core polarization brings the quantum defect. The energy levels of the nS and nD states of Cs atoms can be represented by the modified Ritz formula:

$$E_{nl} = E_\infty - R/(n-\mu_{nl})^2 \quad (1)$$

where E_{nl} is the energy of the level with principal quantum number n and angular quantum number l, E_∞ is the ionization limit and equals $31406.46766\,\mathrm{cm}^{-1}$, R is the Rydberg constant ($109736.86254\,\mathrm{cm}^{-1}$ for ^{133}Cs), μ_{nl} is the quantum defect given:

$$\mu_{nl} = \mu_0 + \mu_1/(n-\mu_0)^2 + \mu_2/(n-\mu_0)^4 + \ldots . \quad (2)$$

Considering $n \geq 25$, we can treat the quantum defect as constant for the same angular momentum states when the higher order items of the μ_{nl} expansion are small ($\propto 1/n^{2*i}$, $i = 1, 2, \ldots$) and can be negligible.

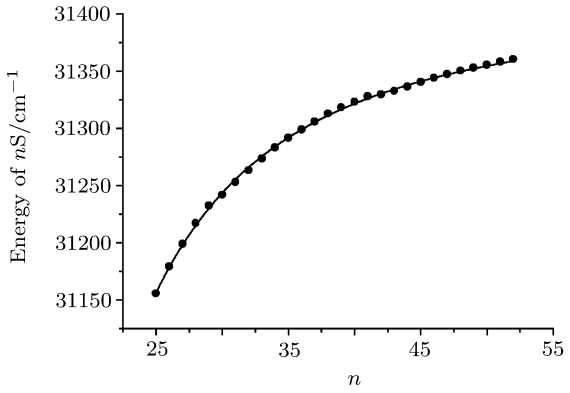


Fig.3. Energy of nS Rydberg states. The dots are experimental data; the solid line is the fitting curve.

So the quantum defect can be exacted according to the energy data E_{nl} of Rydberg states. Here we fit respectively the energy data of nS and nD states shown in Figs.3 and 4 by using the Ritz formula mentioned above and acquire the quantum defects: 4.05219±0.02786 for nS states and 2.46992±0.05492 for nD states.

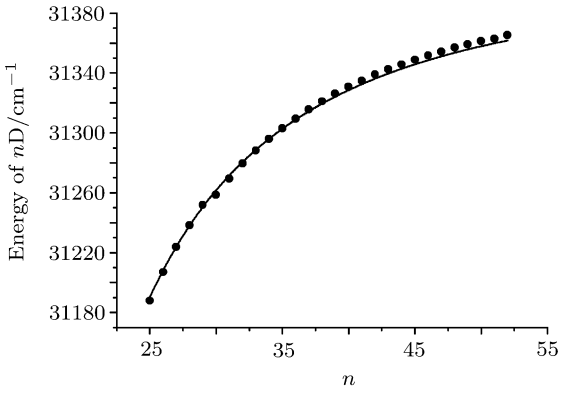


Fig.4. Energy of nD Rydberg states. The dots are experimental data; the solid line is the fitting curve.

The error of data in this work is mainly derived from the line width of the DL beam and the shot to shot fluctuation of laser energy. Moreover, the scan system of DL can bring errors in despite of the fact that we can scan the output wavelengths of DL in the forward and backward direction to reduce the errors in the experiment.

4. Conclusion

In conclusion, we utilize two-photon excitation to obtain high-lying states of nS and nD in a cesium MOT and apply rapid rising-time voltage pulses much higher than the ionization limit of cesium atoms to ionize the Rydberg atoms. High resolution ionization spectra of nS and nD states with principal number n from 25 to 52 are obtained. The energy data of nS and nD are acquired and the quantum defect of nS and nD are given based on the modified Ritz formula.

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S321

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