ARTICLE

Resonance-Enhanced Photon Excitation Spectroscopy of the Even-Parity $3p^5(^2P_{1/2})nl'$ $[K']J$ (l'=1, 3) Autoionizing Rydberg States of Ar

Chun-yan Li[a*], Zhi-wei He[a], Ting-ting Wang[b], Jun-feng Zhen[b], Yang Chen[b*], Jin-song Zhang[c]

a. College of Science, China Agricultural University, Beijing 100083, China
b. Hefei National Laboratory for Physical Sciences at the Microscale and Department of Chemical Physics, University of Science and Technology of China, Hefei 230026, China
c. Department of Chemistry and Air Pollution Research Center, University of California at Riverside, Riverside, CA 92521, USA

(Dated: Received on March 7, 2013; Accepted on April 7, 2013)

Metastable $^{40}Ar^*$ atoms are produced in the two metastable states $3p^54s$ $[3/2]_2$ and $3p^54s'$ $[1/2]_0$ in a pulsed DC discharge in a beam, and are subsequently excited to the even-parity autoionizing resonance series $3p^5np'$ $[3/2]_{1,2}$, $3p^5np'$ $[1/2]_1$, and $3p^5nf'$ $[5/2]_3$ using single photon excitation with a pulsed dye laser. The excitation spectra of the even-parity autoionizing resonance series from the metastable $^{40}Ar^*$ are obtained by recording the autoionized Ar^+ ions with time-of-flight ion detection in the photon energy range of 32500−35600 cm^{-1} with an experimental bandwidth of <0.1 cm^{-1}. A wealth of autoionizing resonances are newly observed, from which more precise and systematic spectroscopic data of the level energies and quantum defects are derived.

Key words: Ar, Pulsed DC discharge, Resonance-enhanced photon excitation spectroscopy, Autoionizing Rydberg resonance

I. INTRODUCTION

The high Rydberg states of rare gases have been a subject of interest to spectroscopists for many years. The rare gases (except helium) possess two relatively closely spaced ionization limits corresponding to the $^2P_{3/2}$ and $^2P_{1/2}$ states of the ion core, with the Rydberg series converging to each of these two limits. The ionization limits and high Rydberg states of the rare gases are of high energy, and spectroscopic studies starting from their ground states require vacuum ultraviolet (VUV) radiation and high-resolution studies are difficult. Promoting one of the np-subshell (n=2−5) electrons of the rare gases to the next available (n+1)s orbital yields four levels that are built on the $np^5(n+1)s$ configuration, namely $np^5(n+1)s$ $[1/2]_{0,1}$ and $np^5(n+1)s$ $[3/2]_{1,2}$. The $np^5(n+1)s$ $[1/2]_1$ and $np^5(n+1)s$ $[3/2]_1$ levels decay radiatively to the ground state, whereas $np^5(n+1)s$ $[1/2]_0$ and $np^5(n+1)s$ $[3/2]_2$ are metastable [1]. The theoretically calculated lifetimes of the two metastable levels of argon, $3p^54s$ $[3/2]_2$ and $3p^54s'$ $[1/2]_0$, are 55.9 and 44.9 s, respectively [1], and the lifetime of the $3p^54s$ $[3/2]_2$ level has been determined experimentally as 38 s [2]. The two metastable levels $3p^54s$ $[3/2]_2$ and $3p^54s'$ $[1/2]_0$ lie at 93143.767 and 94553.665 cm^{-1}, respectively, relative to the argon ground state [3]. This provides an opportunity for excitation to the high lying Rydberg levels via single photon or two photon transitions, which are otherwise not readily accessible from the ground state due to the transition selection rules. Furthermore, these excitation spectra can be obtained with narrow-linewidth laser excitation, thus providing high-resolution studies on the high Rydberg states.

The spectroscopy of high Rydberg states of argon, especially the autoionizing states, has been extensively investigated [3−17]. However, the study of even-parity Rydberg states of argon remains unsystematic and the resolution of the obtained spectra is relatively low [3−9]. In 1973, Stebbing and Dunning first observed the single photon excitation from the second metastable level $3p^54s'$ $[1/2]_0$ to $3p^5(^2P_{1/2})np'$ $[1/2]_1$ (n=11−20), the even-parity autoionizing states of argon [3]. Later they reported the spectra of single photon excitation to the even parity autoionizing state series $3p^5(^2P_{1/2})np'$ $[3/2]_1$ (n=11−26) and $3p^5(^2P_{1/2})nf'$ $[5/2]_3$ (n=9−15), which are excited from the first metastable level $3p^54s$ $[3/2]_2$ [4]. Pellarin *et al.* employed the collinear laser spectroscopy with a field ionization detection technique to investigate the even-parity autoionizing resonances below the first ionization limit, $3p^5(^2P_{3/2})np$, $3p^5(^2P_{3/2})nf$ and $3p^5(^2P_{1/2})np'$ $[1/2]_1$ (n=9, 10), nf' (n=7, 8) $[5/2]_{2,3}$ spectra excited from the $3p^54s$ $[3/2]_2$ metastable level [5]. Muhlpfordt and Even observed a ZEKE spectrum of the $3p^5(^2P_{3/2})np$, $3p^5(^2P_{3/2})nf$, and $3p^5(^2P_{1/2})np'$ ($n\geq15$), $3p^5(^2P_{1/2})$ $nf'(n\geq14)$ Rydberg

*Authors to whom correspondence should be addressed. E-mail: chunyanl@cau.edu.cn, yangchen@ustc.edu.cn, Tel.: +86-551-63606619, FAX: +86-551-63607084

series converging to the two ionization potential excited from the $3p^5 4s\ [3/2]_2$ metastable level respectively, and reported the ionization limits and quantum defects derived from the line position measurements but did not provide the spectroscopic data [6]. Koeckhoven *et al.* observed four-photon excitation from the ground state and the even parity $3p^5(^2P_{1/2})np'$ (n=11−19) $[1/2]_0$, $[3/2]_1$ and nf' (n=10−15) $[5/2]_2$, $[7/2]_4$ autoionizing Rydberg series [7]. Peter *et al.* reported the experimental and theoretical investigation of even $3p^5(^2P_{1/2})np'$ autoionizing resonances of argon np' (n=13, 14) $[1/2]_1$, $[3/2]_2$ [8]. Lee *et al.* reported some np' and nf' autoionizing series by stepwise excitations from instant intermediate states with lasers and synchrotron radiation [9]. The odd-parity autoionizing states of Ar have been studied [10−17] mainly by means of a VUV laser multiphoton excitation or a synchronization radiation of Ar from its ground state to the target states of interest.

Although many experiments have been done for the Ar autoionizing Rydberg states including $3p^5np'$ and $3p^5nf'$, there are few high-resolution spectroscopic studies [3−9]. In the present work, the metastable $Ar^*(3p^5 4s\ [3/2]_2$ and $3p^5 4s'\ [1/2]_0)$ atoms are produced by a pulsed high-voltage DC discharge, and they are then excited to the even-parity autoionizing resonances series $3p^5np'\ [3/2]_{1,2}$, $3p^5np'\ [1/2]_1$, and $3p^5nf'\ [5/2]_3$ by a pulsed UV laser radiation with a narrow bandwidth of $<0.1\ cm^{-1}$. These autoionizing resonance states subsequently decay to Ar^+ ions, which are detected using the time-of-flight (TOF) mass spectrometry. The excitation spectra of the autoionizing resonance series are recorded in the form of the Ar^+ ion intensities as a function of excitation UV laser radiation. More even-parity autoionizing $3p^5np'\ [3/2]_{1,2}$, $[1/2]_1$, and $3p^5nf'\ [5/2]_3$ Rydberg levels are observed in this study. The high-resolution excitation spectra are systematically analyzed, and new results for the resonance energies, quantum defects, are derived from the observed resonance spectra.

II. EXPERIMENTS

The experiment was conducted in a laser ionization mass spectrometer described in the previous publication [17, 18]. Briefly, the photoionization experimental apparatus includes the metastable Ar^* atoms source and the ion detection system. The metastable Ar^* atoms were produced by a DC discharge of a mixture of 5% SF_6 in Ar at a stagnation pressure of 5 atms. The DC discharge source is composed of a pulsed nozzle (General Valve) with a 0.5 mm orifice diameter and a pair of parallel copper plate electrodes with the orifice diameters of 1 and 1.5 mm downstream from the nozzle. Two Teflon disks were used to insulate the nozzle and the two copper electrodes. The gas mixture passed through the nozzle and the two electrodes. A pulsed high voltage of about 2 kV was supplied to the electrodes producing a discharge in the area of the orifices of the copper electrodes. The supersonic beam after the DC discharge was collimated by a skimmer (ϕ=3 mm) and entered into the photoexcitation and photoionization chamber. To remove the ions produced in the DC discharge from the molecular beam, an electric field perpendicular to the beam was applied above the skimmer to deflect the ions out of the neutral beam. The photoionization chamber was maintained at typical pressures of $\sim 1.0\times10^{-4}$ and $<1.0\times10^{-5}$ Pa, respectively, with and without the operation of the beam.

A Nd:YAG laser (Spectra Physics, GCR-190) pumping a dye laser (Lumonics, HT-500) operated with the dyes Rhodamine 590+rhodamine 610 and rhodamine 610+rhodamine 640 was used as the light source (pulse duration of UV radiation is about 8 ns, energy per UV pulse is typically 1.0 mJ). The dye laser output was frequency doubled with a second harmonic generator (Lumonics, HT-1000) and then focused perpendicularly on the metastable Ar^* beam by a 250 mm focal length lens. Ions generated via autoionizing process at the ionization zone were introduced and accelerated to the flight tube of the TOF mass spectrometer and then detected by micro-channel plates (MCP). The mass resolved ion signal from the MCP was amplified by an amplifier (Stanford Research System, SR445) and averaged by a digital oscilloscope (Tektronix, TDS3032B) or a computer data acquisition system. A multi-channel delay pulsed generator was used to control the relative time delays among the nozzle, the laser, and the DC discharge.

The mass resolved photoexcitation spectra in our experiment were obtained by setting the corresponding time gate to monitor the arrival of m/z=40 ($^{40}Ar^+$) ions and recording the ion signals as a function of laser wavelength. No attempt was made to normalize the spectral intensity with respect to the laser power. The typical scan speed of the dye laser was 0.001 nm/s at a 10 Hz laser repetition. Calibration of the laser wavelength was achieved by a wavelength meter (Coherent).

III. RESULT AND DISCUSSION

The excited levels of the rare gas are designated in the $j_c l[K]_J$ coupling scheme [19−22], in which the orbital angular momentum l of the excited electron is weakly coupled to the total angular momentum j_c (3/2 or 1/2) of the $np^5 j_c$ ionic core to yield the resultant quantum angular momentum K. K is then weakly coupled with the spin s of the excited electron giving total angular momentum J. The propensity rules for electric dipole transitions in the jK-coupling scheme are: ΔJ=0, ±1; ΔK=0, ±1 and Δj=0. These rules are well observed, and wherever $\Delta J=\Delta K=+\Delta l$, the transition lines possess higher intensity. However, the Δj=0 rule is not followed strictly, since transitions with a change of the

DOI:10.1063/1674-0068/26/03/259-264

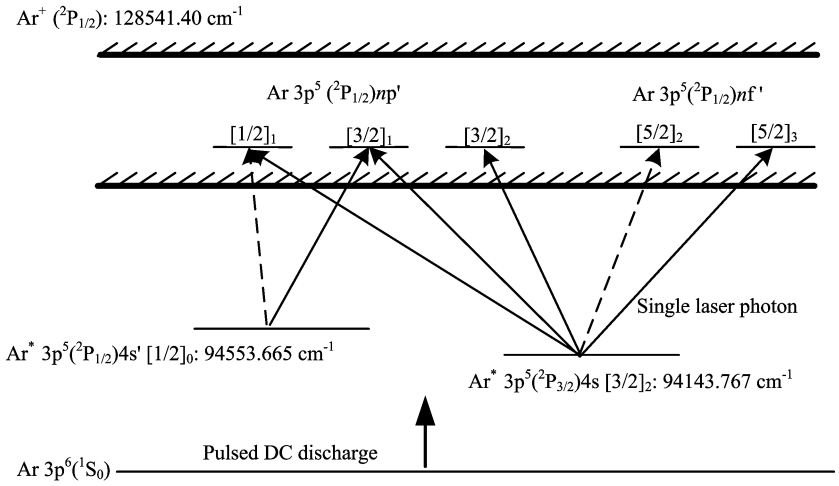

FIG. 1 Schematic diagram of the metastable argon excitation processes. The full arrows indicate the excitation processes observed in our experiment; the broken arrows are for the excitation processes that are allowed by the selection rules but are not observed in our experiment.

ionic core are also often observed.

The principal interest in this work is the autoionizing states. The Ar metastable states ($3p^54s$ $[3/2]_2$ and $3p^54s'$ $[1/2]_0$) are produced by the DC discharge of Ar, and then the autoionizing states in current work are excited from the two metastable Ar* states by one photon resonance transition. Since the first adiabatic ionization potential of Ar is 127109.8 cm^{-1}, only one photon in the current laser wavelength range (280−308 nm) is needed to excite the two Ar metastable states to the autoionizing states of interest. These observed autoionizing states converge to the $^2P_{1/2}$ limit and decay to the first adiabatic ionization limit $^2P_{3/2}$. The following electric-dipole transitions are expected for the observed Ar transitions:

$$3s^23p^5\left(^2P_{3/2}\right)4s\,[3/2]_2 \xrightarrow{h\nu} 3s^23p^5\left(^2P_{1/2}\right)np' \quad (1)$$

$$\xrightarrow{h\nu} 3s^23p^5\left(^2P_{1/2}\right)nf' \quad (2)$$

$$3s^23p^5\left(^2P_{1/2}\right)4s'\,[1/2]_0 \xrightarrow{h\nu} 3s^23p^5\left(^2P_{1/2}\right)np' \quad (3)$$

According to the propensity single-photon transition selection rules, the possible autoionizing resonance series excited from the metastable state $3p^54s$ $[3/2]_2$ are $3p^5(^2P_{1/2})np'$ $[1/2]_1$, $[3/2]_1$, $[3/2]_2$ and $3p^5(^2P_{1/2})nf'$ $[5/2]_2$, $[5/2]_3$, and the possible series excited from the $3p^54s'$ $[1/2]_0$ metastable level include $3p^5(^2P_{1/2})np'$ $[1/2]_1$, $[3/2]_1$. Figure 1 shows the simplified levels and excitation scheme of Ar*. The relevant excitation processes from the metastable levels are denoted by full and broken arrows. The full arrows indicate the excitation processes observed in our experiment, and the broken arrows are for the excitation processes that are allowed by the selection rules but not observed in our experiment. Note although Stebbing and Dunning [3] reported the $3p^5(^2P_{1/2})np'$ $[1/2]_1$ (n=11−20) levels from the single photon excitation of the metastable $3p^54s'$ $[1/2]_0$, the $3p^5(^2P_{1/2})np'$ $[1/2]_1$ levels excited from $3p^54s'$ $[1/2]_0$ are not observed in this experiment. The excitation spectra in the laser energy region between 32500 and 35600 cm^{-1} are recorded by monitoring the autoionized Ar^+ ion intensity, as shown in Fig.2 and Fig.3. The Ar^+ ion intensities of the two figures are plotted in the same scale, with the spectral features in Fig.2 being much weaker.

As shown in Fig.2 and Fig.3, there are five series of autoionizing structure converging to the $^2P_{1/2}$ ionic limit in the current one-photon excitation spectra from the Ar metastable states $3p^54s$ $[3/2]_2$ and $3p^54s'$ $[1/2]_0$. It is known, when ΔJ=ΔK=$+\Delta l$ the excitation spectrum lines possess higher intensity, therefore in the photon energy region of 32500−34000 cm^{-1} the $3p^5$ $(^2P_{1/2})$ np' series excited from $3p^54s'$ $[1/2]_0$ should be the $3p^5np'$ $[3/2]_1$ series, with the following excitation transition (Fig.2)

$$3p^5(^2P_{1/2})4s'[1/2]_0 \xrightarrow{h\nu} 3p^5(^2P_{1/2})np'[3/2]_1 \quad (4)$$

In the higher photon energy there are three closely-spaced $3p^5np'$ series ($3p^5(^2P_{1/2})np'$ $[1/2]_1$, $[3/2]_1$ and $[3/2]_2$) excited from $3p^54s$ $[3/2]_2$ (Fig.3). Based on the analysis in the lower laser photon energy region, we can determine one term energy series ($3p^5np'$ $[3/2]_1$) of the three. With ΔJ=ΔK, the $3p^5np'$ $[3/2]_2$ series should possess the highest intensity of the three. Therefore we can determine the observed three $3p^5(^2P_{1/2})np'$ autoionizing resonance series. There are two $3p^5nf'$ series in the high energy region. Following ΔJ=ΔK, the $3p^5nf'$ $[5/2]_3$, instead of $3p^5nf'$ $[5/2]_2$, should be more likely the observed autoionizing resonance series excited from $3p^54s$ $[3/2]_2$. In addition, the $3p^5nf'$ $[5/2]_2$ series is very close to the $3p^5nf'$ $[5/2]_3$ series [5], and it is

DOI:10.1063/1674-0068/26/03/259-264

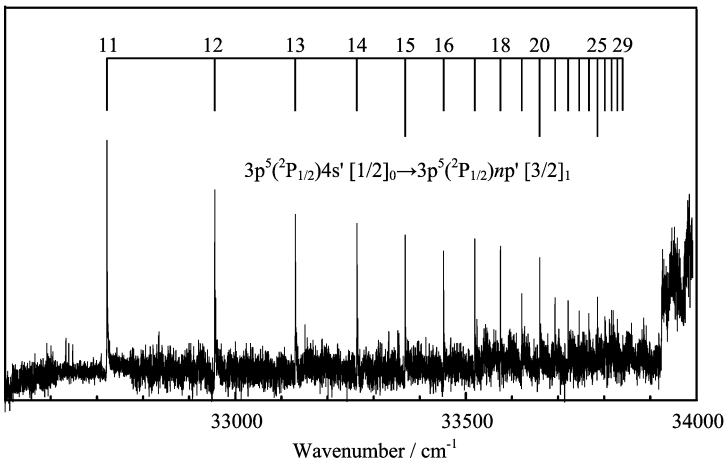

FIG. 2 Excitation spectrum from the Ar^* metastable level $3p^5 4s'\ [1/2]_0$.

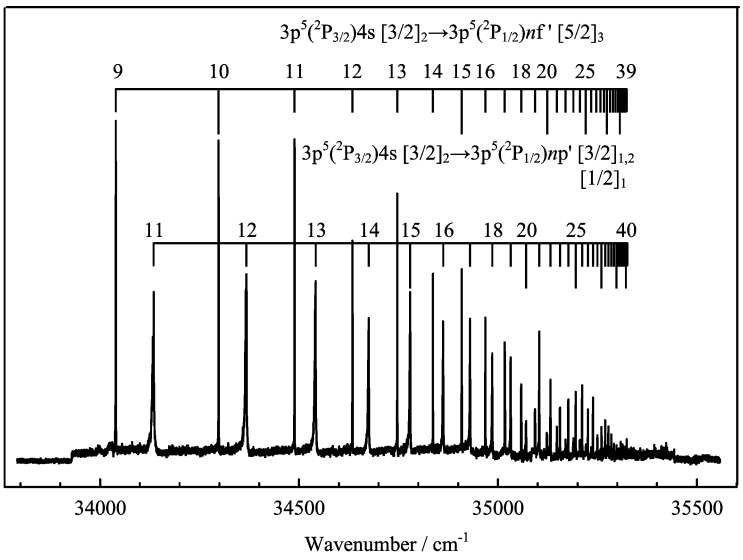

FIG. 3 Excitation spectrum from the Ar^* metastable level $3p^5 4s\ [3/2]_2$.

difficult to distinguish them. Based on the transition rules and the threshold for direct photoionization from the Ar^* metastable to the autoionizing resonance series, the observed series of the autoionizing structures in Fig.2 and Fig.3 are identified as follows

$$3p^5(^2P_{1/2})4s'[1/2]_0 \xrightarrow{h\nu} 3p^5(^2P_{1/2})np'[3/2]_1 \quad (5)$$

$$3p^5(^2P_{3/2})4s[3/2]_2 \xrightarrow{h\nu} 3p^5(^2P_{1/2})np'[3/2]_{1,2}, [1/2]_1 \quad (6)$$

$$3p^5(^2P_{3/2})4s[3/2]_2 \xrightarrow{h\nu} 3p^5(^2P_{1/2})nf'[5/2]_3 \quad (7)$$

The observed spectrum intensity of a given upper $np'\ [3/2]_1$ level from the 4s $[3/2]_2$ level is typically 10 times greater than that of the corresponding transition from the $4s'\ [1/2]_0$ level. If one assumes that these two transitions have similar probabilities, the spectrum intensities would reflect the relative populations of the two metastable levels produced in the DC discharge. Furthermore, by following the $\Delta J{=}\Delta K{=}{+}\Delta l$ rule, the transition $4s'\ [1/2]_0 \xrightarrow{h\nu} np'\ [3/2]_1$ should have higher transition probabilities, indicating that the relative population ratio of the two metastable levels 4s $[3/2]_2$ and $4s'\ [1/2]_0$ is more than 10. It is noted that the transition probability for the upper np' and nf' series from the 4s $[3/2]_2$ level maintain a certain ratio.

The observed term energy values of the $3p^5 np'$ and $3p^5 nf'$ configuration autoionizing levels, obtained with reference to those of the two metastable levels, are listed in Table I and Table II, respectively. The quantum defects δ are obtained by the Rydberg formula [6]:

$$E = \mathrm{IP} - \frac{R(^{40}\mathrm{Ar})}{(n-\delta)^2} \quad (8)$$

DOI:10.1063/1674-0068/26/03/259-264

TABLE I Experimental resonances term energy (cm^{-1}), principal quantum numbers n, and quantum defects δ of the $3p^5np'$ configuration autoionizing Rydberg states of Ar excited from $3p^54s$ $[3/2]_2$.

n	$[3/2]_1$[a]	δ	$[3/2]_2$[a]	δ	$[1/2]_1$[a]	δ	$[3/2]_1$[b]	$[3/2]_2$[b]	$[1/2]_1$[c]
11	127275.60	1.689	127278.62	1.678	127276.42	1.686	127275.74	127278.47	127273
12	127509.11	1.690	127511.51	1.678	127509.98	1.685	127509.39	127511.36	127508
13	127683.96	1.687	127685.66	1.676	127684.60	1.683	127683.90	127685.45	127686
14	127817.41	1.689	127818.97	1.675	127818.37	1.680	127817.52	127819.20	127812
15	127921.94	1.690	127923.08	1.678	127922.59	1.683	127922.28	127923.26	127926
16	128005.46	1.690	128006.34	1.679	128005.98	1.684	128005.77	128006.60	128010
17	128073.39	1.688	128073.85	1.680	128073.49	1.686	128073.40		128068
18	128128.63	1.695	128129.64	1.675	128129.40	1.680	128129.05		128128
19	128174.93	1.696	128175.74	1.677					128169
20	128213.71	1.700	128214.63	1.674	128214.02	1.692			128212
21	128247.02	1.693	128247.68	1.671					
22	128275.16	1.698	128275.72	1.677	128275.68	1.678			
23	128299.49	1.702	128299.71	1.682					
24	128320.53	1.710	128320.76	1.699					
25	128339.11	1.709	128339.29	1.699					
26	128355.32	1.716	128355.45	1.707					
27	128369.61	1.726	128369.77	1.714			128369.61		
28	128382.27	1.740	128382.59	1.714			128382.88	128382.80	
29	128393.80	1.736	128394.12	1.703			128394.35	128394.52	
30			128403.95	1.744				128404.68	
31			128413.20	1.743				128413.72	
32			128421.51	1.746				128422.18	
33			128428.82	1.779				128429.64	
34			128435.64	1.789				128436.44	
35			128441.95	1.783				128442.31	
36			128447.13	1.882				128448.28	
37			128452.44	1.879				128453.32	
38			128457.40	1.857				128458.05	
39			128461.62	1.913				128462.60	

[a] The experimental data ($\pm$0.1 cm^{-1}) in this work.
[b] Experimental results in Ref.[9] ($\pm$0.1 cm^{-1}) from instant intermediate states.
[c] Experimental results in Ref.[3] ($\pm$6 cm^{-1}).

Here E is the observed term energy, n is the principal quantum number, δ is the quantum defects for the series of states, $R(^{40}Ar)$=109735.808 cm^{-1} is the Rydberg constant of argon [14], and IP is the ionization potential of argon. IP($^2P_{3/2}$)=127109.80 cm^{-1} when the ion is left in the j_c=3/2 state, and IP($^2P_{1/2}$)=128541.40 cm^{-1} when the ion is in j_c=1/2. The derived quantum defects are also listed in Tables I and II. The series quantum defects increase as the principal quantum number n increase, besides some irregularity. The quantum defect reflects how much the average potential experienced by the Rydberg electron deviates from a pure Coulombic point charge interaction. The experimental data illuminate that the Rydberg electron penetrates closer to the nuclei with higher quantum number. Since the autoionizing resonances lie between the two ionization potentials in the $^2P_{3/2}$ continuum, the perturbation arising from interactions among the resonance series having the same parity and J, and the perturbation arising from interactions with the $^2P_{3/2}$ continuum, are complex. The perturbation influences the Rydberg electron of Ar and manifests on the variation of the principal quantum defects. The irregularities in the quantum defects for a given series are frequently observed, as shown in Dunning and Stebbing's results [4]. The width of the spectrum peak reflects the lifetime of the resonance. The experimental results show that, as the principal quantum number n increases, the quantum defects of the given series increase whereas the widths of the autoionizing peaks corresponding to the given series decrease. This is expected because the interaction with the $^2P_{3/2}$ contin-

DOI:10.1063/1674-0068/26/03/259-264

TABLE II Experimental resonances term energy (cm^{-1}), principal quantum numbers n and quantum defects δ of the $3p^5nf'$ configuration autoionizing Rydberg states of Ar excited from $3p^54s\ [3/2]_2$.

n	$[5/2]_3$[a]	δ	$[5/2]_3$[b]	$[5/2]_3$[c]	n	$[5/2]_3$[a]	δ	$[5/2]_3$[b]	$[5/2]_3$[c]	n	$[5/2]_3$[a]	δ	$[5/2]_3$[b]	$[5/2]_3$[c]
9	127183.33	0.011	127183.4	127181	19	128236.88	0.014	128237.3		29	128410.49	0.036		
10	127441.65	0.010	127441.5	127437	20	128267.70	−0.027	128267.0		30	128417.84	0.187		
11	127632.60	0.011	127632.6	127636	21	128291.89	0.024	128292.6		31	128425.64	0.198		
12	127778.13	0.009	127777.9	127774	22	128313.47	0.055	128314.7		32	128432.70	0.212		
13	127890.87	0.011	127891.0	127891	23	128333.26	0.033	128334.1		33	128439.64	0.145		
14	127980.45	0.012	127980.7	127982	24	128349.66	0.071	128351.0		34	128445.81	0.100		
15	128052.78	0.012	128053.1	128049	25	128364.74	0.069	128366.0		35	128450.38	0.260		
16	128111.93	0.013	128112.3		26	128378.08	0.071	128379.3		36	128455.71	0.193		
17	128161.09	0.011	128161.4		27	128390.87	−0.009			37	128460.17	0.223		
18	128202.20	0.011	128202.5		28	128401.50	−0.017			38	128464.14	0.288		

[a] The experimental data ($\pm 0.1\ cm^{-1}$) in this work.
[b] Calculated results in Ref.[3] ($\pm 6\ cm^{-1}$).
[c] Experimental results in Ref.[4] ($\pm 8\ cm^{-1}$).

uum is greater near threshold.

IV. CONCLUSION

We have carried out the experiment study of the autoionizing $3p^5np'$ and $3p^5nf'$ resonance series of argon by using pulsed DC discharge along with single UV photon excitation and the TOF-MS technique. We have presented new data on the Rydberg autoionizing levels of argon excited from the two metastable levels $3p^54s\ [3/2]_2$ and $3p^54s'\ [1/2]_0$, from which more systematic information on the level energy values and quantum defects of Ar were derived.

V. ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (No.51007092).

[1] N. E. Small-Warren and L. Y. Chiu, Phy. Rev. A **11**, 1777 (1975).
[2] H. Katori and F. Shimizu, Phy. Rev. Lett. **70**, 3545 (1993).
[3] R. F. Stebbing and F. B. Dunning, Phys. Rev. A **8**, 665 (1973).
[4] F. B. Dunning and R. F. Stebbing, Phys. Rev. A **9**, 2378 (1974).
[5] M. Pellarin, J. L. Vialle, M. Carre, J. Lerme, and M. Aymer, J. Phys. B **21**, 3833 (1988).
[6] A. Muhlpfordt and U. Even, J. Chem. Phys. **103**, 4427 (1995).
[7] S. M. Koeckhoven, W. J. Burma, and C. A. de Lange, Phys. Rev. A **51**, 1097 (1995).
[8] T. Peter, T. Halfmann, U. Even, A. Wunnenberg, I. D. Petrov,V. L. Sukhorukov, and H. Hoptop, J. Phys. B **38**, S51 (2005).
[9] Y. Y. Lee, T. Y. Dung, R. M. Hsieh, J. Y. Yuh, Y. F. Song, G. H. Ho, T. P. Huang, W. C. Pan, I. C. Chen, S. Y. Tu, A. H. Kung, and L. C. Lee. Phys. Rev. A **78**, 022509 (2008).
[10] J. Z. Wu, S. B. Whitfield, C. D. Caldwell, M. O. Krause, and P. van der Meulen, Phys. Rev. A **42**, 1350 (1990).
[11] D. Klar, K. Harth, J. Ganz, T. Kraft, M. W. Ruf, H. Hotop, V. Tsemekhman, and M. Y. Amusia, Z. Phys. D **23**, 101 (1992).
[12] S. M. Koeckhoven, W. J. Burma, and C. A. de lange, Phys. Rev. A **49**, 3322 (1994).
[13] J. Landais, M. Huet, H. Kucal, and T. Dohnalik, J. Phys. B **28**, 2395 (1995).
[14] N. K. Piracha, M. A. Baig, S. A. Khan, and B. Suleman, J. Phys. B **30**, 1151 (1997).
[15] J. M. Weber, K. Ueda, D. Klar, J. Kreil, M. W. Ruf, and H. Hotop, J. Phys. B **32**, 2381 (1999).
[16] J. Bommels, J. M. Weber, A. Gopalan, N. Herschbach, E. Leber, A. Schramm, K. Ueda, M. W. Ruf, and H. Hotop, J. Phys. B **32**, 2399 (1999).
[17] X. F. Zheng, T. T. Wang, and Y. Chen, Chin. J. Atom. Molecul. Phys. **21**, 605 (2004).
[18] C. Y. Li, T. T. Wang, J. F. Zhen, Q. Zhang, and Y. Chen, Chin. J. Chem. Phys. **21**, 401 (2008).
[19] G. Racah, Phys. Rev. **62**, 438 (1942).
[20] I. I. Sobelman, *Atomic Spectra and Radiative Transitions*, Berlin Heidelberg: Springer-Verlag, (1979).
[21] R. D. Cowan, *The Theory of Atomic Structure and Spectra*, Berkeley: University of California Press, (1981).
[22] R. D. Knight and L. G. Wang, J. Opt. Soc. Am. B **3**, 1673 (1986).

DOI:10.1063/1674-0068/26/03/259-264