Lifetimes of $2p^53p$ and $2p^53d$ Levels in Ti XIII

Kozo ANDO*, Yaming ZOU*†, Susumu KOHMOTO*, Tadashi KAMBARA*,
Yohko AWAYA*, Tadao TONUMA*, Takashi NIIZEKI*††,
and Seiji TSURUBUCHI**

* The Institute of Physical and Chemical Research (RIKEN),
Wako, Saitama 351-01, Japan

** Tokyo University of Agriculture and Technology,
Koganeishi, Tokyo 184, Japan

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安藤 剛三*, ヱー ヤーミン*, 河本 進*, 神原 正*,
栗屋 容子*, 戸沼 正雄*, 新関 隆*††, 鶴淵 誠二**

* 理化学研究所 和光市 〒351-01

** 東京農工大学理学部 小金井市 〒184

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Decay curves for three $2p^53s$ - $2p^53p$ and eight $2p^53p$ - $2p^53d$ transitions of neonlike Ti XIII have been measured using the beam-foil technique. The experimental lifetimes of two $2p^53p$ and seven $2p^53d$ levels have been obtained. Decay curves of $3p$ levels have been analyzed by using the ANDC (Arbitrary Normalized Decay Curve) method taking into account the cascade transitions and those of $3d$ levels have been done by multiexponential fitting. The results are compared with another experimental data set and some theoretical values.

1. Introduction

Neonlike spectra of heavy ions have interested both experimentally and theoretically for a number of years mainly because of the possibility to use certain transitions for diagnostic purposes in high temperature plasmas¹⁻³⁾. Recently, the $3s$ - $3p$ transitions have shown in the successful demonstration of laser amplification at soft X-ray wavelengths in many neonlike ions of Cu to Mo, which are presented in reviews^{4,5)}. The

spectral lines of multiplets, for which amplification has been achieved, are different from the ones predicted by computer simulations for such laser schemes, possibly because of incompleteness of the detail knowledge of the term structure, transition probabilities and collision rates in neonlike ions⁵⁾.

The energy level structure has been theoretically studied along the isoelectronic sequence⁶⁻¹²⁾, and identifications and term analysis of the neonlike titanium ion have been carried out for the transition arrays $2p^53s$ - $2p^53p$ and $2p^53p$ - $2p^53d$ ¹³⁻¹⁵⁾.

Some of the $2p^53p$ and $2p^53d$ lifetimes in Neisoelectronic sequence have been experi-

† Permanent address: Shanghai Jiao Tong Univ., Shanghai, China

†† Permanent address: Faculty of Sci. Tokyo Inst. of Tech., Meguro-ku, Tokyo, Japan

mentally determined on Na II¹⁶⁾, Mg III¹⁷⁾, Al IV¹⁸⁾, Si V¹⁹⁾, S VII^{20, 21)}, Cl VIII²²⁾, Ar IX^{21, 23, 24)}, Ti XIII²⁵⁾, and Cr XV²⁶⁾. Cascading effect of $2p^33d$ levels for estimating lifetimes of $2p^33p$ levels was compensated by the ANDC (Arbitrary Normalized Decay Curve) method²⁷⁾ in Cl VIII²²⁾, S VII²¹⁾ and Ar IX²¹⁾. Theoretical estimates of lifetimes or transition probabilities along the Ne isoelectronic sequence have been given in references^{6, 28-32)}.

In the other experimental work of Ne-like Ti²⁵⁾, decay curves had been analyzed in two ways, one was multiexponential fitting (allowing for the spatial resolution) of one to three components by varying initial parameters (including relative amplitudes and decay times) in a wide range, the other way was to extract the primary lifetime by using some approximated theoretical values of branching ratios and lifetimes of cascading levels.

In this work, the ANDC method was used to extract the primary lifetimes of two $3p$ levels for eliminating the cascading effect. The multiexponential fitting method³³⁾ was also used, both for data smoothing of the cascade and primary decay curves of $3s$ - $3p$ transitions and for analyzing the decay curves of $3p$ - $3d$ transitions.

2. Experiment

The beam-foil decay curve measurements were performed at RILAC (RIKEN heavy ion linear accelerator). Ti³⁺ ions were accelerated to 38 MeV to obtain maximum production of neonlike Ti¹²⁺ ions after passing through a $10 \mu\text{g}/\text{cm}^2$ carbon foil. The light emitted by the excited Ti¹²⁺ ions was observed with a 2.2 m grazing incidence spectrometer (McPherson 247) with a grating of 600 grooves/mm, and then detected by a ceratron with a CsI coated cathode. The entrance slit of $70 \mu\text{m}$ was placed at 10 mm from the beam center, and then the spatial resolution of 0.2 mm (correspond to the time resolution of 16 ps) was obtained. Experimental arrangement is shown in Fig. 1.

Spectral lines of Ti XIII were identified in spectra obtained with a spectral resolution of about $0.5 \text{ \AA}$, by changing Ti-ion energy of 21, 27 and 38 MeV. Identification of

Fig. 1. Schematic diagram of the experimental setup.

spectral lines, classification and the coupling scheme of levels of $3s$, $3p$, and $3d$ followed Jupén and Litzén¹⁴⁾, that is, the $3s$ levels are expressed by jj -coupling and the $3p$ and $3d$ levels are done by LS -coupling.

In decay curve measurements, a carbon foil was moved with steps in the range of 0.05–0.5 mm. Intensities of decay curves were normalized to the charge integrals which were collected by a Faraday cup. The “aging” effect of the carbon foil was monitored by an optical fiber linked to a photomultiplier. The ion beam velocity was estimated by the magnetic field strength of the analyzing magnet, before starting the experiments. This velocity agrees with that measured by the time of flight method within 2%.

We have measured the decay curves of eleven spectral lines, in which eight lines were $3p$ - $3d$ transitions and three lines were $3s$ - $3p$. The other lines were too weak to measure decay curves, or were mixed with other unknown lines. The energy diagram and the observed transitions are shown schematically in Fig. 2.

Since the usable time of the RILAC accelerator is limited, the measured time lengths of the decay curves are around 0.5 nsec for $3p$ - $3d$ transitions and around 1–2.2

Fig. 2. Schematic level diagram of the $2p^33s$, $3p$, and $3d$ levels in Ti XIII. Singlet levels have their J -value followed by the letter s . The spectral lines measured decays are indicated with their wavelengths in Å.

nsec for $3s$ - $3p$ transitions, except for 4.3 nsec in the case of the 365.7 Å ($3p^3P_2$ - $3d^3D_3$) decay.

3. Analysis of Decay Curves and Results

Decay curves of $3s$ - $3p$ transitions have complex forms as shown typically in Fig. 3, which shows the decay curve for 437.2 Å line of $3s(3/2, 1/2)_2$ - $3p^1D_2$ transition. For $3p$ - $3d$ transitions, decay curves seem to be rather simple. As an example, the decay curve of 365.7 Å line of $3p^3P_2$ - $3d^3D_3$ transition is shown in Fig. 4.

The decay curves of the $3p$ - $3d$ transitions were fitted with the sum of exponential decays [$\exp(-\lambda_i t)$] using the program DISCRETE³⁵⁾. The maximum number of the exponents is 4 and a lifetime is deduced from the inverse of λ_i of the main component. The results are shown in Table 1. Each decay curve of $3p$ - $3d$ transitions includes a short-lived component of a lifetime between 11 and 24 ps, with the exception of the $3d^1F_3$ decay estimated from the 366.5 Å line. These are typical lifetimes of direct cascades to $3d$ levels from the upper

Fig. 3. Decay curve of the 437.2 Å line of $3s(3/2, 1/2)_2$ - $3p^1D_2$ transition. Solid line represents a five-component fit to the data.

Fig. 4. Decay curve of the 365.7 Å line of $3p^3P_2$ - $3d^3D_3$ transition. Solid line represents a multiexponential fitting of four components.

levels $n \geq 4$. These lifetimes are so small that the measured lifetimes are not affected obviously by those direct cascading. The influence of $2s2p^3I$ cascades is considered to be small for the same reason.

For the decay curve of the line at 365.7 Å ($3p^3P_2$ - $3d^3D_3$), a long lifetime was detected, because this decay curve had a sufficiently intense long tail, and this long-lived com-

ponent is interpreted as indirect cascades from many higher-lying levels. Thus the obtained lifetime of the 3d ³D₃ level is considered to be most reliable, because the decay curve included the whole cascades. Long-lifetime cascades could not be detected for other decay curves from 3d levels, because sufficient tails were not observed. As a result, the estimated lifetime will be longer than it should be, because the long lifetime component can not be separated from other components by multiexponential fitting. Therefore, the accuracy of measured lifetimes of the 3d levels is mainly limited by the relatively short time length.

In order to estimate the error of the lifetimes caused by the short tail, the decay

curve of the 365.7 Å line was cut at typical time of 0.5 nsec and was analyzed by the multiexponential fitting. The cut decay curve has two exponential components similar to the other short decay curves. The obtained lifetime and cascade component were 0.179 ± 0.005 and 0.024 ± 0.002 ns, respectively. As expected, this lifetime is larger by 23% than that of the original decay curve. Therefore, any lifetime obtained by analysis of a decay curves of short tail is overestimated by about a similar percentage.

The two levels of 3p ¹D₂ and 3p ³D₃ are fed by direct cascade transitions from 3d levels. The lifetimes of 3d levels are of the same order of magnitude as those of

Table 1. Lifetimes (ns) of 2p⁵3d and 2p⁵3p levels in Ti XIII

Upper level	Wavelength [Å]	Experimental lifetimes		Theory
		This work	Other work ²⁵⁾	
3d ³ F ₄	369.5	$0.188 \pm 0.002 (0.015 \pm 0.010)^a$	0.115 ± 0.010	0.158 ^d , 0.114 ^e , 0.109 ^f 0.158 ^g , 0.113 ^h , 0.107 ⁱ
3d ³ F ₃	359.3	$0.173 \pm 0.005 (0.019 \pm 0.004)^a$	0.112 ± 0.010	0.156 ^d , 0.105 ^e , 0.102 ^f 0.174 ^g , 0.104 ^h , 0.100 ⁱ
3d ³ F ₂	362.5	0.148 ± 0.081 $(0.023 \pm 0.021, 2.02 \pm 27)^a$	0.111 ± 0.010	0.142 ^d , 0.101 ^e , 0.099 ^f 0.142 ^g , 0.102 ^h , 0.100 ⁱ
3d ¹ F ₃	366.5	0.181 ± 0.002^a	0.115 ± 0.012	0.147 ^d , 0.105 ^e , 0.102 ^f
3d ³ D ₃	343.8	$0.204 \pm 0.007 (0.028 \pm 0.003)^a$		0.177 ^g , 0.106 ^h , 0.107 ⁱ
	365.7	0.137 ± 0.003 $(0.011 \pm 0.003, -0.006 \pm 0.003, 2.25 \pm 0.16)^a$	0.111 ± 0.010	0.147 ^d , 0.108 ^e , 0.105 ^f 0.175 ^g , 0.108 ^h , 0.107 ⁱ
3d ¹ D ₂	354.7	$0.153 \pm 0.003 (0.013 \pm 0.0005)^a$	0.105 ± 0.010	0.142 ^d , 0.101 ^e , 0.099 ^f 0.142 ^g , 0.101 ^h , 0.100 ⁱ
3d ³ P ₂	336.0	$0.212 \pm 0.005 (0.024 \pm 0.005)^a$	0.115 ± 0.010	0.154 ^d , 0.116 ^e , 0.109 ^f 0.152 ^g , 0.110 ^h , 0.106 ⁱ
3p ¹ D ₂	459.3	0.279 ± 0.013^b $[0.312 \pm 0.010 (-0.055 \pm 0.029)]^a$	0.215 ± 0.020	0.225 ^c , 0.329 ^d , 0.201 ^e 0.203 ^f , 0.276 ^g , 0.201 ^h
	437.2	0.264 ± 0.042^b $[0.196 \pm 0.116 (-0.11 \pm 0.13, 0.035 \pm 0.036, -0.006 \pm 0.002, 1.05 \pm 0.22)]^a$		0.254 ⁱ
3p ³ D ₃	474.6	0.289 ± 0.003^b	0.240 ± 0.013	0.236 ^c , 0.290 ^d , 0.242 ^e
		$[0.363 \pm 0.013 (-0.15 \pm 0.013)]^a$		0.242 ^f , 0.288 ^g , 0.237 ^h 0.260 ⁱ

- Results of multiexponential fitting. Cascading lifetimes are given in parentheses. Multiexponential fitting results of 3p levels are present in square brackets for comparing with the ANDC results. A negative sign denotes a growing-in cascade.
- Results of ANDC analysis.
- Results of Crance⁶⁾
- Results of Bureeva and Safronova²⁶⁾.
- Results of MCDF explained in the text.
- Results of Bhatia *et al.*⁷⁾
- Results of Pokleba and Safronova²⁹⁾.
- Results of Loginov³²⁾.
- Results of Gulov and Ivanova³³⁾.

the primary 3p levels, so that the cascade transitions have the strong effect on the decay curve of 3s-3p transition. The ANDC method can reduce the cascade effect in decay curve by simultaneously analyzing the primary decay and their direct cascade decays. The analysis by the ANDC method can be carried out by the program CANDY³⁴⁾. Before applying the CANDY program, multiexponential fitting equations of the primary decay curve of 3s-3p transition and of their cascade decay curves of 3p-3d transitions were calculated using the program DISCRETE. These fitting equations were used as the input data for CANDY program. In this way the decays of 3p 1D_2 and 3p 3D_3 were corrected for cascading by performing an ANDC method using the program CANDY. The ANDC results are stable with respect to the criteria discussed by Engström³⁴⁾, and the values of lifetimes are shorter than those given by multiexponential fitting. It is desirable to include the whole direct cascade in the ANDC analysis, but only some of the main cascades have been measured, because some of the spectral lines of the cascades were not identified due to very small transition probabilities. This may not affect the accuracy of the lifetimes of measured 3p levels, because, as discussed by Engström³⁴⁾, the result of ANDC analysis would be unstable if main cascades had not been taken into account. Results are given in Table 1.

4. Theoretical Calculation of Lifetimes

We performed an *ab initio* calculation of the relativistic Multi-Configuration Dirac-Fock (MCDF) type with the computer code of Grant and coworkers³⁶⁾ on Ti XIII. The probabilities of dipole transitions of 2p⁵3s-2p⁵3p and 2p⁵3p-2p⁵3d were calculated. All calculations of level energies were made in the so-called extended average level (EAL) mode and include the configuration interaction with 2s2p⁶3s, 2s2p⁶3p, and 2s2p⁶3d. QED corrections³⁷⁾ are included in all results. The results of level energies are coincident with the experimental data within 0.2% and with results of Cogordan and Lunell¹⁰⁾ within 0.02% except for 3p 1S_0 and

3d 1P_1 . Moreover, the average deviation between calculated and observed wavelengths is approximately 1 Å. The levels of 3p 1S_0 and 3d 1P_1 needs a special handling in calculation⁹⁾, but these levels are not concerned in this experiment. The lifetime is calculated from the sum of probabilities of transition from the same upper level. Results are given in Table 1.

5. Discussion

The multiexponential fitting of the 3p level decays can not give proper lifetimes, since the lifetime of the 3p level are close to those of the cascading 3d levels. However, the results of ANDC/CANDY appear as reliable, as already discussed by Engström³⁴⁾ and Westerlind *et al.*²²⁾. The lifetimes of the 3p 1D_2 level obtained from two different decay branches coincide very well within estimated errors.

The lifetime of the 3d 3D_3 deduced from the multiexponential fitting of decay curve is reliable, because the decay curve was measured up to long tail and included the whole cascades. Other lifetimes of 3d levels are overestimated by about 20% because of short tail as mentioned above.

In Table 1 the lifetimes obtained in our experiment are compared with those of other work²³⁾ and with theoretical values. For the 3p levels and the 3d 3D_3 level the differences of lifetimes between ours and other experimental results are more than the estimated errors and are about 20%. For other 3d levels the differences of lifetimes are 6 to 32% if taking into account the overestimation due to the short tail.

Those differences may be caused by the different time window in the measurement and the different analytical procedure. A time window is depends on a spatial resolution. In our experiment the spatial resolution was 0.2 mm, and the corresponding time window is 16 ps. Our time resolution is about 10% of the typical lifetime of the 3d level, so that the measured lifetime of the 3d level may give a little large value because of no time window correction. While in other experiment, the spatial resolution was much larger than ours, but a

correction for it has been made in analysis of decay curves³⁸⁾.

Theoretical lifetimes were calculated by many different methods. Crance⁹⁾ used the semi-empirical method of a parametric potential. Bhatia *et al.*⁷⁾, whose level assignment is different from that of Jupén and Litzén¹⁴⁾, used an *ab initio* calculation without any configuration interaction. Bureeva and Safronova²⁸⁾ and Pokleba and Safronova²⁹⁾ performed *ab initio* calculation in the framework of the Z-expansion technique. Loginov³²⁾ used the semi-empirical method of a parameter fitting. Gulov and Ivanova³³⁾ used the relativistic perturbation theory.

The theoretical values given by Bureeva and Safronova²⁸⁾ and Pokleba and Safronova²⁹⁾ are in better agreement with our results. The theoretical values of Gulov and Ivanova³³⁾ agree with ours only for the $3p$ levels. Other theoretical results are shorter.

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